MODELING AND ANALYSIS OF IMPACT OF SEPAK TAKRAW BALL ON THE PLAYER'S HEAD

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UNIVERSITY OF MALAYA

KUALA LUMPUR

2013

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THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2013

UNIVERSITI MALAYA

ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: ISKANDAR

Registration/Matric No: KHA070027

Name of Degree: DOCTOR OF PHILOSOPHY

Title of Project Paper/Research Report/Dissertation/Thesis ("this Work"):

MODELING AND ANALYSIS OF IMPACT OF SEPAK TAKRAW BALL ON THE PLAYER'S HEAD

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ACKNOWLEDGEMENTS

First and foremost, all praises and thanks are to Allah SWT, the Lord of *'Alamin* (mankind, jinn, and all that exists) and peace be upon the Master of the Messengers, Muhammad SAW.

I would like to express my sincere gratitude and appreciation to the following people for their invaluable assistance and support throughout my studies.

My heartfelt thanks and deepest appreciation is to my supervisor, Prof. Dr. Zahari Taha for his encouragement, assistance, and careful and wise guidance in the writing of my thesis. At all of our meetings, he had provided constructive comments and good counseling which had helped me in more ways than I can describe. I am greatly indebted for the opportunity and the generosity that he had given me to be able to work at the consultant office, CPDM (Center for Product Design and Manufacturing). This chance had given me the financial support and the significant contribution in conducting this research.

My sincere thanks are also to my co-supervisor, Associate Prof. Dr. Nukman Yusoff, who has also offered support and encouragement for me to complete my studies. He has provided profound supervisions and the guidance in the writing of my thesis.

I owe a great deal to my friends: Prof. Dr. T. M. Indra Mahlia, Assoc. Prof. Tuan Mohammad Yusoff Shah, Mr. Norhafizan Ahmad, Mr. Raja Ariffin, Dr. Husni Usman, Dr. Iqbal Mochtar Lutfi, Dr. Yap Hwa Jen, Dr. Salwa Hanim, , Dr. Hilma Raimona, Dr. Krismadinata, Dr. Novita Sakundarini, Dr.Sugiyono, Dr. Syafie Syam, Dr. Gesang Nugroho, Dr. Sulaiman Ali, Dr. Lee Jer Vui, Dr. Sarkawt Rostam, Dr. Azuddin Mamat, Dr. Farzad Tahriri, Dr. Nader Ale Ebrahim, Tuw Tze Khai, Ali Jannifar, Aznijar Ahmad-Yazid, Muhammad Tadjuddin, Teuku Firsa, Nazaruddin, Mukhtar Yunus, Zulkefle Kassim, Jamali Md Sah, Rossi Passarella, Hartomo, Aliq Zuhdi, Hassan Alli, Ruhaizin Sulaiman, Sugoro Bhakti Sutono, Ikhwan Gazali, Muhammad, Koh Kok Hian, Ho Fu Haw, Said Amir Azan, Fadli Usman, Fauzan Amin, Sofyan Umar, Mirta Widia, Sazlina, Maryam, Lydyaty, and colleagues at the Department of Engineering Design and Manufacture in the University of Malaya whose support, advice, opinions and attention that they have given to me when I faced problems at work and in writing my thesis. I also appreciate my friends who were willing to be the subjects for data of my research.

I wish to thank the University of Malaya in Kuala Lumpur for the facilities provided and for the good services from their administrative staff. I am also deeply grateful to Universitas Syiah Kuala in Banda Aceh for the leave of absence that was granted to me to pursue my studies. I also would like to thank all the lecturers in the Fakultas Teknik, especially in Jurusan Mesin, for their invaluable support. The opportunity to study and obtain a Doctor of Philosophy degree shall prepare me for a better future so that I can well serve my country and society.

My mother, Fauziah Barawas, and my sisters, Dr. Ika Fikriah, M. Kes. Nurullita, SE, Dewi Andalia, and Diana Fauzia Sari, Spd. M.A. My brothers-in-law, Ir.Suheriyatna, M.M. and Faisal Amir, and also my sisters-in-law Fitriani Insanuri, ST. M.Eng and Nouval Hayani, SE., who have been very compassionate and encouraging throughout my studies. I thank them from the bottom of my heart for their sympathy, deep understanding and devotion. My late father, Drs. Hasanuddin Husin, have always been my inspiration in achieving my goals. I show deep gratitude to my parents in law, Associate Prof. Dr. Qismullah Yusuf, M.Ed. and Dra. Ainul Mardhiah Rasyid, for their precious support and encouragement.

Finally, I dedicate this thesis to my wife, Yunisrina Qismullah Yusuf, Spd, M.Ling, and our three beautiful daughters, Kaisah Ghufrani, Syamim Az-Zahra and Naurah Fatima, for their continuous support, love and patience. It is an undeniable fact that my family gave me the motivation to complete this study.

ABSTRACT

Sepak takraw is a traditional game played at the international level in Asia. The game is played using various parts of the body, except the hands. Most notably, the head is often used. Unlike soccer, no studies have yet been conducted on injuries caused by contact between the ball and the head for this sport. This research was initiated following the incidents of 24th SEA Games in Korat, Thailand, 2007, in which the Malaysian Sepak Takraw Association (PSM) had pulled out of the championship. The withdrawal was due to complains of headaches from the players believed to be caused by the sepak takraw ball used in the competition. Thus, the objectives of this research are to investigate the phenomena of ball-to-head impact and the level of the head injury on sepak takraw players, as well as to develop scalp, skull, cerebrospinal fluid (CSF) and brain model by using finite element model.

The scope of this research include interviews of 100 players (questionnaire based) and data collection of ball velocity and contact positions of heading from various Sepak Takraw championships in Malaysia in 2012. The three models of heading were front-forehead, side-forehead and top-forehead impact and its effect observed on the frontal-brain and occipital-brain. Furthermore, analysis of the sepak takraw ball characteristics, drop test ball for impact on skull dummy and drop test free fall heading for validation were also conducted. The modelling and finite element analysis of the human head was further performed.

The findings from the interviews revealed that after hard headings, 88% of the players experienced headaches, 64% felt emotional, 65% had tears coming out of their eyes, 68% heard droning sounds and 67% felt unbalanced. From the survey, it was found that the maximum speed of the sepak takraw ball before heading was 13.58 m/s

and from simulation the maximum impact force on the head was 688.1 N, causing a maximum of brain displacement of 0.80 mm. The maximum magnitude of acceleration at the centre of gravity of the brain was found to be 1674.5 m/s^2. The corresponding Head Injury Criterion (HIC) is 210.1 and the Head Impact Power (HIP) is 11.6 kW.

Based on studies by Newman et. al. (2000), this implies probabilities of 42% for HIC and 39% for HIP that sepak takraw players will experience Mild Trauma Brain Injury (MTBI) from hard headings of fast speed sepak takraw balls. Therefore, this study suggests that every player should wear a head protection to reduce the impact during heading.

ABSTRAK

Sepak takraw adalah sejenis permainan tradisional yang dimainkan di peringkat antarabangsa di Asia. Permainan ini dimainkan dengan menggunakan pelbagai bahagian badan, kecuali tangan. Paling ketara, kepala lebih sering digunakan. Tetapi tidak seperti bola sepak, tiada kajian telah dilakukan ke atas kecederaan yang disebabkan oleh sentuhan antara bola dan kepala untuk permainan ini. Kajian ini telah dimulakan hasil aduan daripada pemain semasa Sukan SEA ke-24 di Korat, Thailand, 2007. Persatuan Sepak Takraw Malaysia (PSM) telah menarik diri dari kejohanan setelah pemain mengadu sakit kepala. Objektif kajian ini adalah untuk menyiasat fenomena kesan bola-ke-kepala dan tahap kecederaan kepala pada pemain sepak takraw, serta untuk membangunkan model kulit kepala, tengkorak, cecair serebrospina (CSF) dan model otak dengan menggunakan model unsur terhingga.

Kaji selidik ini dilakukan melalui temu bual bersama daripada 100 pemain Sepak Takraw dan pengumpulan data had laju bola takraw dan kedudukan tandukan bola takraw di kepala pada saat menanduk yang di ambil dari kejohanan. Tiga jenis model yang digunakan adalah tanduk depan dahi, dahi samping dan dahi atas tanduk diperhatikan dari otak occipital dan frontal. Selain dari pada itu, analisis ciri-ciri bola sepak takraw, menjatuhkan bola takraw untuk ujian keberkesanan ke atas tengkorak tiruan dan ujian pengesahan juga dijalankan. Pemodelan dan analisis unsur terhingga kepala manusia juga telah dijalankan.

Hasil daripada kajian temu bual tersebut selepas menanduk bola takraw yang laju, 88% daripada pemain mengalami sakit kepala, 64% merasakan emosi, 65% air mata keluar, 68% mendengar bunyi bising dan 67% merasakan tidak seimbang. Dari kaji selidik dan simulasi, telah didapati bahawa kelajuan maksimum bola takraw sebelum menuju kepala ialah 13.58 m/s, daya impak maksimum pada kepala adalah 688.11 N,

maksimum anjakan otak adalah 0.80 mm, dan hasil pecutan otak di pusat graviti adalah 1674.5 m/s^2. Selain itu, Kriteria Kecederaan Kepala (HIC) adalah 210.1 dan Kuasa Impak Kepala (HIP) adalah 11.366 kW.

Berdasarkan Newman et. al. (2000), dapat disimpulkan bahawa kebarangkalian 42% untuk HIC dan 39% untuk HIP daripada pemain sepak takraw boleh mendapatkan Kecederaan Otak Trauma Ringan (MTBI) setelah menanduk bola takraw dengan kelajuan cepat. Oleh yang demikian, dicadangkan bahawa setiap pemain perlu memakai pelindung kepala untuk mengurangkan kesan semasa menanduk.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol:

s = displacement (m)

v = velocity (m/s)

a = linear acceleration (m/s^2)

I = mass moment of inertia (Nms^{-2})

m = mass (kg)

t = time (sec)

F = force (N)

r = radius

θ = angular displacement (degree or radian)

ϕ = rotation vector

ω = angular velocity (rad/s)

α = angular acceleration (rad/s^2)

ρ = density (kg/m^3)

E= Young's modulus (Pa)

v = Poisson's ratio

Abbreviation:

ASDH: Acute SubDural Hematoma

ASTAF: Asian Sepak Takraw Federation

CNS: Central Nervous System

CSF: Cerebrospinal Fluid

DAI: Diffuse Axonal Injury

FEA: Finite Element Analysis

HARP: Harmonic Phase

HIC: Head Injury Criterion

HIP: Head Impact Power

ISTAF: International Sepak Takraw Federation

LOC: Loss of Consciousness

MRI: Magnetic Resonance Imaging

MTBI: Mild Traumatic Brain Injury

SIS: Second Impact Syndrome

INTRODUCTION

1.1 Background

Sepak Takraw or ‘kick volleyball’ is a popular sport of South-East Asia, in which players maintain a sepak takraw ball in the air by using their feet, knee, chest and head to touch the ball. Figure 1.1 shows the players in the court of a Sepak Takraw game.

Figure 1.1: Sepak Takraw game.

Lopez et. al. (1993) stated that the specific origin of Sepak Takraw is unclear, although in the Philippines, the Muslims were considered the first to play a form of this game known as *Sipa*. It was played by kicking a rattan ball, although without any specific rules. From 1891 to 1920, the game was then played in a circle without a specified area. It was performed basically for exercising the body for cooperative skills, improving swiftness and stretching stiff limbs after a long day of work. At the time, Sipa was quite popular in Manila and other neighboring provinces.

The professional evolution of the sport started in 1829 when the Siam Sports Association drafted the first rules of the game. In the next four years, they added a volleyball style net and held the first public competition of Sepak Takraw in the country.

In 1960, delegations from Indonesia, Malaysia, Laos, Singapore, and Thailand met in Kuala Lumpur to standardize the regulations of the sepak takraw game and to form the Asian Sepak Takraw Federation (ASTAF). The federation held the first international Sepak Takraw competition in Malaysia in 1965 at the Southeast Asian Peninsular Games (SEAP Games), the precursor of today's Southeast Asian Games (SEA Games).

In 1990, Sepak Takraw was included at the Asian Games in Beijing. Afterwards, women also took part with the first women's championships hosted in Thailand in 1997. Attempts have been made to acquire the Olympic recognition for the game, with no success so far. Nevertheless, Sepak Takraw is one of the fastest growing sports in Asia to date. In the board of the International Sepak Takraw Federation (ISTAF), 35 countries have already participated in the super series tournaments.

Presently, Thailand dominates almost all international competitions of the past few decades. Other prominent teams are from Malaysia, Indonesia, Myanmar, South Korea, Singapore and Vietnam.

1.1.1 Sepak Takraw Game

In Sepak Takraw, the ball is passed across a chest-high net by opposing teams by using any part of the body except the hands and arms. In general, the rules of the game are similar to volleyball; the main objective is to land the ball on the floor inside the boundaries of the opposing team's court.

A Sepak Takraw team consists of 3 players, namely, a *tekong* (server), a *feeder*, and a *killer/spiker*. Generally, the tekong will serve the first ball while the feeder normally passes the ball or sets the ball to the killer or spiker to execute the finishing move to the opponent's side.

In this sport, exchanges of the ball occur at high speeds and extreme acrobatic moves are often employed. The moves well known in Sepak Takraw are (from http://takraw.webark.org):

- *Service:* The act of putting the ball into play by the tekong. When a ball is taken for service, two kinds of service techniques are employed namely *sila* and *kuda*. The ball speed from *kuda* is known to be a faster service compared to the other. Usman et. al. (2004) reported a slightly higher mean post-contact ball linear velocity of 19.33 m/s for *kuda* service and 17.44 m/s for *sila* service.
- *Spike:* A powerfully hit shot directed into the opponent's court using either the foot or head. This includes the four basic skills which is the inside kick, the knee and thigh kicks, the header, and the front kick.
- *Sunback Spike:* A spike in which the player jumps with his back to the net and kicks the ball over the same shoulder as the kicking foot, similarly in soccer this is known as the *bicycle kick*.
- *Block:* Blocking is a defensive skill used to counter a spike coming from close to the net. A block is usually made by jumping in the air and raising a leg and/or back to divert the ball back into the opponent's court.
- *Heading*: To "kick" the ball that comes higher than the waist with the head. The top forehead, front forehead and side forehead are often involved.

1.1.2 Sepak Takraw Ball

The traditional sepak takraw ball is made from hand weaved bamboo or rattan into a sphere-shaped ball. In 1982, Marathon Intertrade Co., Ltd. modernized the sport by introducing woven synthetic (plastic) balls with the basic materials from polypropylene. This has standardized the ball characteristics as the previously used hand woven rattan ball had variations in weights and weaving complexities.

Based on the guideline of the International Sepak Takraw Federation (2004), the plastic balls for takraw must have a covering of 12 holes and 270 intersections with 18 strips (Ahmad et. al., 2012), the circumference measurement must be within 42–44 cm for men and 43–45 cm for women, and the weight ranges from 170–180 g for men and from 150–160 g for women. The evolutionary development of the sepak takraw ball designs are shown in Figure 1.2.

Figure 1.2: Sepak takraw ball: rattan ball (left[1], middle[2]) and synthetic ball (right)

1.2 Statement of Problem

There is a possibility that repeated impacts with the synthetic plastic sepak takraw ball may result in traumatic injury to the players. This assumption was highlighted when the Malaysian Sepak Takraw Association [Persatuan Sepaktakraw Malaysia or PSM] objected the use of rubber-coated rather than rattan balls in the 24th SEA Games in Korat, Thailand in 2007, and subsequently withdrew from the competition (Utusan Malaysia, 20/12/2007). This was due to complains of headaches from Arif Basu, a Malaysian spiker, who required rests after every training sessions and needed subsequent medical treatments. The head of PSM, Tengku Adnan Tengku Burhanudin, had said, “this ball is inherently dangerous and can cause injury, even in

[1] Source: http://tenpesos.com/sepak-takraw-in-the-philippines-2/
[2] Source: source:netprosports.com

training sessions. Imagine if a player have to head the ball 100 times during intensive training ” (Utusan Malaysia, p. 1, 20/12/2007).

Accordingly, this study evaluates the probability of concussions due to impacts of sepak takraw ball on the player’s head. A concussion is a trauma-induced change in mental status, with or without unconsciousness caused by an impact to the head or upper body, or by non-contact severe motion, such as whiplash. Its symptoms range from a mild headache, nausea, dizziness, vertigo, heightened sensitivity to light or sound, amnesia to prolonged unconsciousness. A person who has had one concussion is four to six times as likely to have a second concussion as a non-concussed player (Taha et. al., 2008). The second concussion is often significantly more severe than the first, even if the second impact is seemingly minor, because the brain has not completely healed from the first concussion yet. This is often called the second impact syndrome (SIS).

Newman et. al. (2000) found that severity of head injury was correlated to the magnitude of the kinetic energy rate when the head experienced an impact. Their study was based on clashes of players in American Football. Meanwhile, the Consumer Product Safety Commission (CPSC) (1995) found that 12.6% of concussion cases are were related to soccer. Furthermore, Delaney et. al. (2002) reported more than 60% of college soccer players experience concussion symptoms in a single season.

Studies on head impacts by sepak takraw balls have been conducted by some researchers in recent years. Taha et. al. (2008) focused on experimental evaluation of the head impact power from low speed balls. Subsequently, Taha et. al. (2010) had also applied a photogrammetric method to measure the head impact power on Sepak Takraw players. Another study by Ahmad et. al. (2012) was on the impact of sepak takraw balls thrown at a flat surface based the finite element analysis. Thus far, no computational studies have been made on the impact of takraw balls on the head of its players due to ball headings. Therefore, this study intends to fill in that research gap to include comprehensive computational modelling and analysis using Finite Element Analysis (FEA) and appropriate comparisons with experimental tests.

1.3 Objectives of Research

In general the objectives of this research are to indentify the level of injury on the sepak takraw players based on their headings as follows:

1. To develop Finite Element (FE) models of the scalp, skull, Cerebrospinal Fluid (CSF) and brain.
2. To validate the speed of sepak takraw balls, contact time of heading, impact force of the head and acceleration on the brain from drop-test experiments and finite element methods.
3. To analyze the impact of the sepak takraw ball on the players' head using Finite Element Analysis (FEA).
4. To determine the extent of head injury on sepak takraw players based on Head Injury Criterion (HIC) and Head Impact Power (HIP).

1.4 Scope of Research

This study was conducted in collaboration with the Malaysian Sepak Takraw Association. It will focus primarily on the head impact conditions based on the Malaysian playing style/techniques and players, both of professionals and amateurs. It will also cover the modeling and analysis of the finite element model (FEM) of the human head impact from sepak takraw balls. In addition, this study includes:

- Questionnaires and interviews of the players on head/brain injury symptoms, positions of ball heading on the head, and the number of ball headings during training.

- Measurements of the anthropometric of the head data from the players for use in 3D model of the head.
- High speed image capture from the sepak takraw championships in Malaysia in 2011 and 2012 to measure actual speeds of the sepak takraw ball before heading in the first service, contact times during heading, and locations of heading on the head.
- Drop tests of sepak takraw ball impacts on a dummy skull to obtain the accelerations on the brain, contact times of heading, speeds of sepak takraw ball and impact forces. The results are then compared with FE simulation results.
- Modelling of the top scalp of the human head, skull, general cerebrospinal fluid and general brain using CATIA and analysis using Abaqus CAE software.
- Validation by experiments and simulations of the accelerations, contact times of heading, speeds of sepak takraw ball before and after heading and impact forces on the head.

1.5 Organization of Thesis

This thesis is arranged in the following sequence:

Chapter 1 presents the background of Sepak Takraw, the problem statement for this study, objectives, scope and organization of the thesis.

Chapter 2 focuses on the literature review related to the present study which comprises of the definitions of head injury and a review on previous studies of head injury in sports, including Sepak Takraw. The biomechanics head injury assessment, the basic parameter measurements such as of linear kinematics, angular kinematics, forces and moments are presented. The photogrammetric method, head injury in sport, specifically in Sepak Takraw is also provided.

Chapter 3 presents the selected research framework and data collection methods. The experimental design, experimental procedure and apparatus for the experimental study are described. Similarly, the computational analysis technique using FEA is presented and the subsequent validation between the FEA simulations and experimental methods are explained.

Chapter 4 presents the result of surveys from the interviews with Sepak Takraw players, which included the background of players, Mild Traumatic Brain Injury (MTBI) symptoms, sepak takraw ball speeds, and the frequency of headings during practices and locations of heading on the head during practices. Furthermore, the findings from observations at the Sepak Takraw World Cup 2011 are discussed.

Chapter 5 discusses the FEA results on head dummy drop-test simulation, front-forehead heading simulation, top-forehead heading simulation and side-forehead simulation. The results would show the displacements, velocities, and accelerations of brain, impact forces on head, head injury criterion and head impact power.

Chapter 6 presents the results of finite element analysis of head impact by low speed balls. A comparison of the impact force, acceleration, contact time and speed of sepak takraw ball before and after heading between experiment and finite element analysis are also presented and discussed.

Chapter 7 presents the concluding remarks, conclusions, major contributions and recommendations for future work.

LITERATURE REVIEW

2.1 Introduction

This chapter presents the review of head injuries in sports and in particular, Sepak Takraw. An overview is presented on the mild trauma brain injuries in sport players and its assessments. It further elaborates the parameter of measurements on human motion which consists of linear kinematics, angular kinematics, forces and moments. The head injury criterion (HIC) and head impact power (HIP) are explained to show how they can be used as predictors for the level of severity of injury.

2.2 Head Injuries in Sports and Sepak Takraw

A number of studies have found that the rate of head injury occurrences depends on the type of sport played as the equipment and game rules differ from one sport to another. A study by Junge et al. (2006) of sport players whom had participated in the 2004 Olympic Games found that approximately 24% of the injuries reported were head injuries, consisting of mild concussion at 11%, lacerations at 4%, fracture at 2% and contusions at 2%.

As for the type of sports, Junge et al. (2006) further reported that handball accounted for 42% of head injuries, soccer at about 20%, and both basket ball and hockey at 13%. Other reports on head injuries and the type of sports played were on skiing/snowboarding at 3-15% (Hunter, 1999; Levy et. al., 2002), ice hockey at 4-18% (McIntish et. al., 2005), equestrian sport at 19% and boxing at 16% for concussion (Zarzyn et. al., 2003). As for baseball, head trauma accounted for 11% of injuries with another 28% for facial injuries (Yen et. al., 2000).

Preliminary studies of head injuries in Sepak Takraw include that of Taha et. al. (2008). They conducted a study to develop a method of measurement for the Head Impact Power of Sepak Takraw balls. The objective of their study was to compare the

HIP between two balls, where ball 1 was the Marathon brand without rubber and ball 2 was the Marathon brand with impregnated rubber. Subsequently, the HIP values obtained were then compared to Newman et. al. (2000). Newman et. al. (2000) had earlier developed the probability of concussion for different HIP values, where the probability of 5% is 4.7 kW, 50 % is 12.79 kW and 95% is 20.88 kW. The findings from Taha et. al. (2008) revealed that when the balls were being dropped from a height of 3.5 m, the HIP value of ball 1 was 4.42 kW and the HIP value of ball 2 was 7.86 kW. For ball 1, the probability of concussion was less than 5%, whereas for ball 2 the probability of concussion was 20%, a fourfold increase over ball 1. Furthermore in actual competitions, the velocity of the sepak takraw ball was known to reach speeds of up to 160km/hr or 44.4 m/s, thus significantly increasing the probability of concussion to more than 50%.

Next, photogrametrics method was also employed by Taha et. al. (2010) to calculate the HIP of the sepak takraw balls on the players. Photo images from recordings of the sepak takraw ball services received by the players' heads were done during the Sepak Takraw World Cup Championship in Malaysia in May 2009. The upshots showed that the maximum speed of the ball was 17.83 m/s and the maximum HIP was 77.86 kW, which was classified as a possible cause for moderate neurological injuries. The use of head protection for the players was therefore suggested by this study.

Although the majority of sport related head injuries are those of minor or mild concussions, the recovery period should not be taken lightly. Unfortunately, this proper recovery may be overlooked, especially in professional sport category, where players are expected to return to the game as soon as possible. Schmitt et. al. (2007) claimed that prolong a concussion which reoccurs may ruin the brain tissue. It is advised that a player returns to play only after he or she has completely recovered from previous mild concussions.

2.3 Head Injury

The broad term of head injury includes skull fractures and soft tissue damage to the head. To identify the mechanisms involved requires the understanding of the basic components of the human head anatomy. The scalp, which covers the outer surface of the head, has a thickness of about 5-7 layers of soft tissue (Fehrenbach and Herring, 2002). As shown in Figure 2.1 the human head consist of various components that are shielded by the rigid skull to protect the brain from injury.

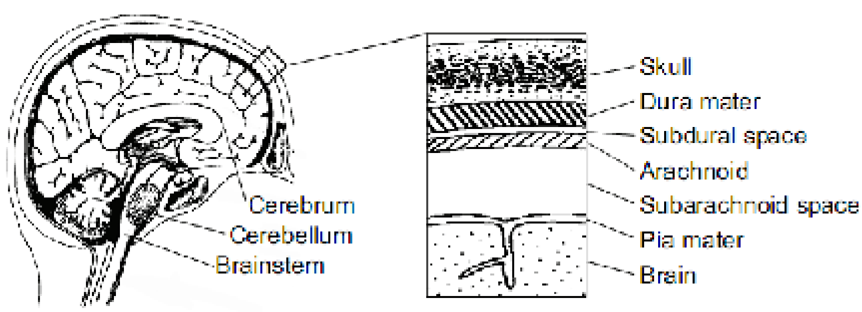


Figure 2.1: Overview of the basic components of the human head, sagittal section of the brain (left) and components of the meninges (right)

(Source: Brands, 2002: 4)

Meninges are three layers of soft tissues located between the skull and brain as shown in Figure 2.1(b). The three layers of the meninges are the dura mater (the outermost layer), the arachnoid, and the pia mater (the inward layer). Dura mater covers the inside of the skull and consists of two special folds, the falx and the tentorium, which divides the brain into sections of left and right, and top and bottom, respectively. The arachnoid is a thin layer of membrane made up of various sizes of delicate tissues and blood vessels. The pia mater is the layer adjacent to the brain surface which hosts the blood vessels connecting to the brain tissue. The space between the dura mater and the arachnoid is called the subdural space, whereas the space between the arachnoid and the pia mater is called the subarachnoid space. The cerebrospinal fluid (CSF) is located in the subarachnoid space.

According to Pike (1990), the CSF acts as a cushion to protect the brain by absorbing shocks under impacts. The human brain consists of three primary parts: the brainstem, the cerebellum, and the cerebrum. The major part of the brain is the cerebrum which is divided by the falx into two halves, the left and right cerebral hemispheres. Each hemisphere consists of the frontal, temporal, parietal and occipital lobes, and each lobe controls different functions of the brain.

Head injury can be classified into two broad categories of either open or closed head injuries, as summarized in Figure 2.2 (Zomeren & Brouwer, 1994). Open head injuries occur when both the scalp and skull are penetrated due to serious skull fractures. Closed head injuries are often referred to as brain injuries when the skull remains undamaged. The severity of the injuries depends on the severity of impacts, which determines the force on the head.

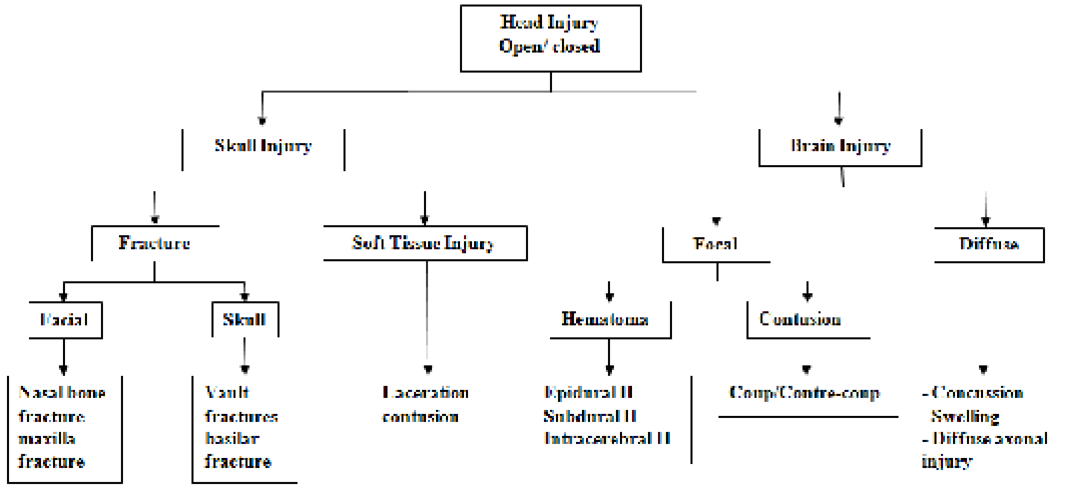


Figure 2.2: Possible injuries to the head.

(Source: Schmitt, 2007: 58)

In medical literature, head injury is at most times used interchangeably with traumatic brain injury (TBI). Thus TBI, in particular, is also referred to as a s*ilent epidemic*. Hitabashi (2007) has shown that about half of traumatic deaths are due to head injuries and the death rate from TBI comprise up to 2%. Amongst those who survive, a majority end with disabilities, including 3% in weakness. The chance of having a good recovery is rated at about 30%. To identify specific brain injuries resulting from various circumstances is essential to reduce the issue of TBI as a public health problem.

2.3.1 Brain Injury

Brain injury is used to indicate acute traumatic damage to the central nervous system (CNS). According to Schmitt (2007), brain injury can be divided into two types which are diffuse and focal injury. Diffuse injury can be further divided into concussion, swelling and diffuse axonal injury. Similarly, focal injury can be divided into two, namely, hematoma and contusion. Three main brain injury mechanisms recognized in modern research are diffuse axonal injury (DAI), cerebral contusion, and acute subdural hematoma (ASDH). However, these are not further discussed because it is not within the scope of this present study.

2.3.1.1 Mild Trauma Brain Injury

Schmitt et. al. (2007) asserted that in sports, mild trauma brain injury (MTBI) is often diagnosed from the players. Previous studies on sport players' head injuries, as reported in section 2.2, have also presented reports on mild concussions experienced by the players.

Schmitt et. al. (2007: 71) defined MTBI as "a complex patho-physiologic process induced by mechanical loading of brain." Generally, it is related to a series of clinical symptoms commonly detected in mild diffuse cerebral injury which includes temporary damage of neurological functions that heals after a few days. However, MTBI requires good treatment and must be monitored considerably because repeated MTBI may result in recurring degenerative brain damage (Biasca et. al., 2006).

Various sporting associations such as the sport group of IOC (International Olympic Committee), FIFA (Federal International Football Association) and IIHF (International Ice Hockey Federation) document the concussions or MTBI of sport players for the development of the Sport Concussion Assessment Tool (Schmitt et. al., 2007).

Facial injuries are common and noticeable in boxing, especially to the eyes. In sports, this is the main cause of concussion as well. Accordingly, the foundation models of the head have been constructed to evaluate the MTBI from this sport. Walilko et. al. (2005) reported that MTBI in boxing is estimated by the load of punches transferred to the head. The subjects of their study consisted of Olympic boxers of different weight classes. The delivered punches to the face were simulated using an instrumented Hybrid

III dummy. Their findings showed that the average punch force was 3427 ± 811 N, the hand velocity was 9.14 ± 2.06 m/s and the effective punch mass was 2.9 ± 2 kg. The peak punch force varied from 1666 N to 6860 N, depending on the boxer's body weight as the force would certainly be higher for the heavier weight class because of higher effective mass of the punch. The peak translational acceleration was 58 ± 13 g, the rotational acceleration was 6343 ± 1789 rad/s^2 and the neck shear force was 994 ± 318 N. The mean HIC calculated from all punches was 71.

Another study on boxing was by Taha et. al. (1985), who conducted experiments on heavyweight boxers by using a ballistic pendulum targeting 7 kg cylindrical metal mass. The study found that, the boxers' fist reached impact velocities of up to 8.9 m/s with a peak impact force of 4096 N and the peak acceleration of the pendulum was 53 g. Smith et. al. (2000) sampled a group of English boxers and had determined that the peak loads was 4800 N for elite, 3722 N for intermediate and 2381 N for novice boxers. By using an instrumented head form, they further measured the accelerations for different types of punches which reached up to 43.6 g for translational acceleration and 675.9 rad/s^2. Although Ommaya (1984) mentioned that assuming tolerance limit of 200g for translational acceleration and 4500 rad/s^2 for rotational acceleration, it is agreed that repeated sub-concussive, although well below the tolerance limits, is the source of MTBI.

Zhang et al. (2004) investigated the occurrence of MTBI in professional football players. The predictors and levels of injury were analyzed based on the results of the brain tissue responses and were associated to the site of MTBI occurrences. The injury predictor suggests that the concussion is caused by the shear around the brainstem region. The shear stress experienced may affect the brain function and lead to injury. It was proposed that a shear stress of 7.8 kPa was the tolerance limit for a 50% probability of sustaining a MTBI. Furthermore, should the head be exposed to combined translational and rotational accelerations (impacts durations between 10 to 30 ms), the suggested tolerance of translational and rotational accelerations were less than 85g and 6000 rad/s^2 , respectively, for reversible brain injury level. The proposed HIC value was 240. Similarly, Pellman et al. (2003) reported that the HIC for NFL (US National Football Leugue) concussion threshold was 250. They concluded that the risk of traumatic brain injury is low from straight blows which induce translational accelerations (less than 2%). Instead, a higher risk is suggested from high rotational accelerations (exceeding the limit of 4500rad/s^2). The model proposed by Zhang et al. (2004) further indicated that intracranial pressure could also serve as a global response indicator for head injury. The intracranial pressure was more influenced by translational accelerations whilst the shear stress in the central part of the brain was more sensitive to rotational accelerations.

Price et. al. (2007) conducted studies on soccer players and found that the measurements of dynamic forces and deformations are strongly affected by impact velocities. Their FE model analysis agreed well with experimentation a results and thus validated the soccer ball impacts. It was expected that their findings may further assist in the future design and development of soccer ball.

Dr. Michael Lipton (as reported by Charlene Laino from scienceray.com in 2011) performed brain MRI scans on 32 amateur soccer players with an average age of 31. It was revealed that the MRI scans of players who head a ball around 1000 to 1500 times a year show the presence of strangeness in brain white matter, specifically those parts that were responsible for memory, attention, planning, organization and vision. Those who head less than 1000 times a year showed no oddities in the brain. He explained that the ball itself does not cause the magnitude of the effects-laden nerve damage in the brain. Thus he added, “we found the real implication for players isn't from hitting headers once in a while, but repetitively, which can lead to degeneration of brain cells" (scienceray.com, 11/29/2011).

A more recent study by Zhang et al. (2013) looks at the outcomes of head-to-ball contacts of young female soccer players on cognitive function by using a tablet-based app they had created for the experiment. A computer screen response test was designed to evaluate their levels of mental alertness. There were 24 female high-school students who participated in the study (median age 16.5 years) of 12 soccer players and 12 non-soccer players. They had normal or corrected to normal vision and no previous head injury or neurological conditions were documented from these participants. Every soccer player were to perform head balls during the practice session before the testing, with median 6 (range: 2–20) head balls per session based on self-reports. The non-soccer player did not perform any head ball before testing. The years of soccer playing were 8 years (range: 5–12) and 11 hours (range: 2–16) for soccer players and none for non-soccer players. The participants were to react to the random appearance of a white square by touching a point on the opposite side of the screen. Their performance was measured by response speed. The results showed that the soccer players were significantly slower than non-players in the performance of pointing away from a target on the screen, but no difference was found in the performance of pointing to a visual target on the screen. Accordingly, tasks that involve pointing away from a target require specific voluntary responses (Anti-Point), whilst pointing to a target is a more reflexive response (Pro-Point). In conclusion, the study suggests that heading a soccer ball, which is believed to be less forceful actions in sports, can cause changes on certain cognitive tasks performances that are consistent with mild traumatic brain injury of the frontal lobes. Thus, they recommended more research to verify whether the changes were permanent or temporary.

2.3.2 Skull Injury

According to Schmitt (2007), skull injury includes fracture (facial and skull) and soft tissue injury (laceration and contusion). The facial skull injury involves damages in the nasal and maxilla structures while a fracture skull injury involves the fractures of the vault and or basilar. However, the focus of this research is on brain injury since skull injury rarely occurs in sport activities. Therefore, the discussion on skull injury is not further reviewed.

2.3.3 Biomechanical Head Injury Assessment

According to Newman et. al. (2000), the threshold for head injury will be exceeded when the rate of change of kinematic energy of the head surpass some limiting value. The recommended functional relation comprise of all six degrees of motion and directional sensitivity characteristics that correlates the rate of change of kinetic energy to head injury probability. Head injury probability is assessed by the index from: "the maximum value that the function achieves during impact is the maximum power input to the head" (Newman et. al., 2000: 362).

2.3.3.1 Head Injury Criterion (HIC)

A closed head injury occurs when the head goes through a change in its motion that goes beyond its capacity to adjust to the change. The kinematics of the head is usually distinguished by its acceleration in time. Brain injury assessment criteria are usually derived from the functional relationships between the severity/probability of brain injury and the acceleration of the head. Studies to assess this relationship have been conducted by examining the reaction of impacts on corpses, animals, volunteers, or victims of accidents.

Previous studies have developed several assessment functions on head injury. Gadd (1966) was among the first to develop the kinematic head injury function which is the Severity Index (SI), with the following equation:

$$SI = \int_T a(t)^{2.5} dt \tag{2.1}$$

where:

a(t) = the linear acceleration of the head in gravitational units

T = the time duration of the head impact in seconds is

The assessment by Gadd (1966) has been implemented by the National Operating Committee on Standards for Athletic Equipment (NOCSAE) for the performance standard of football helmets in 1997.

In 1999, the Federal Motor Vehicle Safety Standard 208 developed another eminent head injury assessment function with the following equation:

$$\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5} (t_2 \quad t_1)_{max} \tag{2.2}$$

$$a = \sqrt{a_x^{2} + a_y^{2} + a_z^{2}} \tag{2.3}$$

where:

a = a resultant head acceleration (m/s^2)

$t_2 - t_1 \leq 36$ ms

$t_{2,}\, t_1$ selected so as to maximize HIC

The trapezoidal rule for integration is used: $I = \int_a^b f(t)dt$

$$I = \frac{(b-a)\left(f(a)+f(b)\right)}{2}$$

(2.4)

Equation 2.2 and Equation 2.3 are derived from Wayne State Concussion Tolerance Curve (WSTC) by Gurdjian, et. al. (1953). Equation 2.2 is directly from Versace's (1971) deliberation from the precision of Equation 2.1.

WST curve is approximated with an empirical expression for which the slope of the Wayne State curve when plotted in log-log coordinates was approximated by –2.5 (Gadd,1966). Therefore, a value of 2.5 appears in Equation 2.2. The following equation relates the average acceleration to time duration:

$$\mathbf{a_{ave}}^{2.5}\,\mathbf{T} - \mathbf{1000} \qquad (2.5)$$

However, from an engineering point of view, it is reasoned that the above expression is not comprehensive as they contain units which do not relate to any recognized measure of impact severity. Up to that time, a proposal by Versace (1971) on other empirical fits to the Wayne State data was considered improved in some time domains than the Gadd approximation. Here, the exponent was set not to 2.5 but just to 2 and the function is:

$$\mathbf{a_{ave}}^{2}\,\mathbf{T} = \mathbf{6737} \qquad (2.6)$$

where:

a_{ave} = expressed in units of m/s^2

Figure 2.3 illustrates the WST curve and the Gadd approximation.

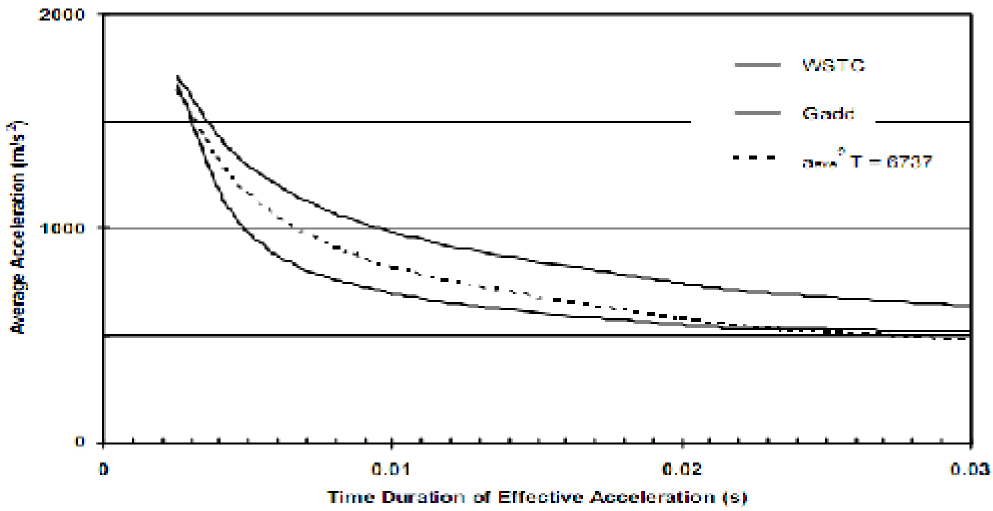


Figure 2.3: Comparison of the Wayne State Tolerance Curve with Approximations

(Source: Newman et. al., 2000: 363)

Equation 2.1 is considered to fit in the 5 to 30 ms range much better than the equation from Gadd. This expression carries a more significant physical meaning.

2.3.3.2 HIC Scores as Predictors of Injury Severity

To estimate injury risk, the automotive industry and others have commonly used the empirically determined relationships between a HIC score of a head impact and the probability of head injury in different severity (National Highway Traffic Safety Administration (NHTSA), 1997; Prasad & Mertz, 1985). This relationship is illustrated in the Expanded Prasad-Mertz Curves as shown in Figure 2.4. It indicates that "each curve estimates the probability that an impact with a given HIC score will result in a specified level of head trauma" (Shorten, 2009: 7).

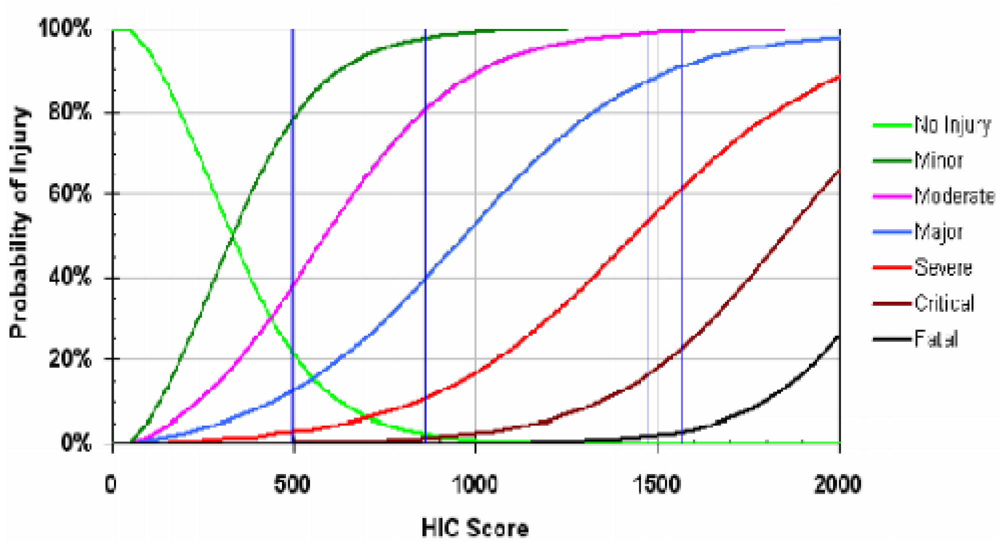


Figure 2.4: Expanded Prasad-Mertz Curves.

(Source: Shorten, 2009: 7)

Among the latest study on relationship of HIC to mild traumatic brain was by Newman et. al. (2000), as shown in Figure 2.5.

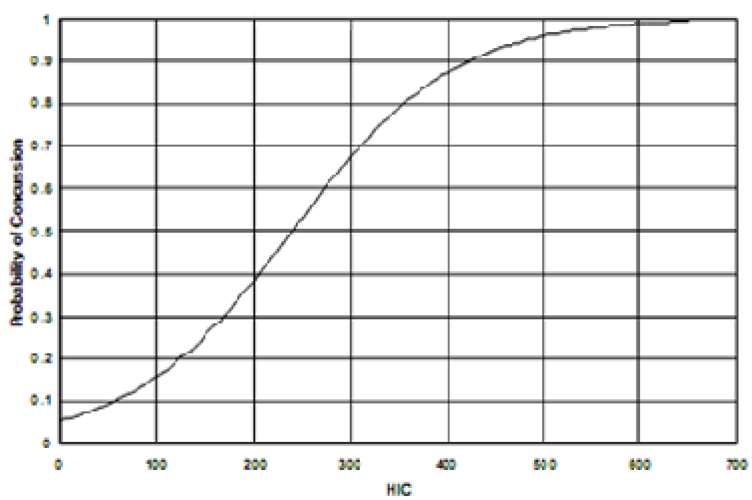


Figure 2.5: Probability of concussion based on HIC

(source: Newman et. al., 2000: 366)

Marjoux et al. (2007) conducted a study to investigate the injury prediction capability of sixty-one real-world accident cases which was reconstructed to provide head acceleration fields and head initial impact conditions to further compute the HIC (Figure 2.6), the HIP (Figure 2.8), the SIMon (the injury mechanisms related criteria provided by the simulated injury monitor) and the ULP criteria (Louis Pasteur University finite element head models). Figure 2.6 shows that HIC starts from 20 to 950 for football player cases, 125 to 3000 for motorcyclist cases and 750 to 3500 for pedestrian cases.

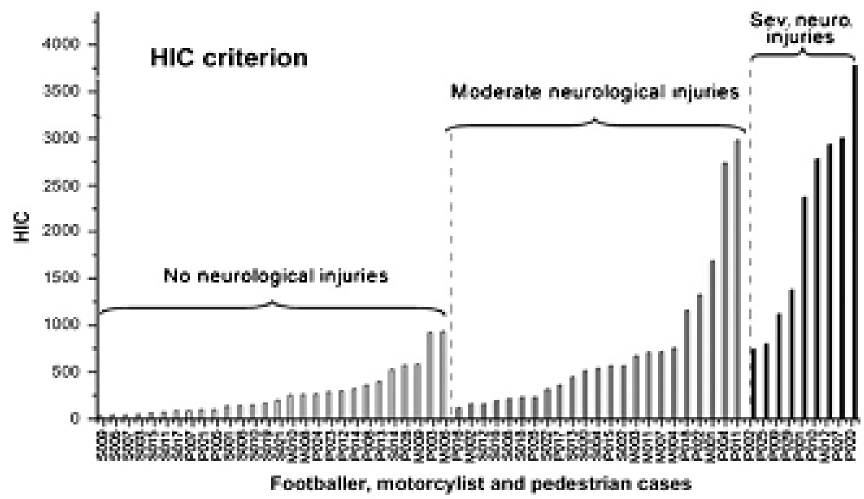


Figure 2.6: Histogram of head injury criterion on footballer, motorcylist and pedestrian cases (Marjoux et al., 2007: 1139)

2.3.3.3 Abbreviated Injury Scale (AIS)

The injury of the head and neck area due to collisions is described by the Abbreviated Injury Scale (AIS). The injury severity can be categorized and subdivided into 6 levels as shown in Table 2.1 (American Association for Automotive Medicine (AAAM), 2005).

Table 2.1: AIS classified head injury

(Source: reproduced from Schmitt et. al., 2007: 59)

AIS	Category	description
1	minor	Skin/scalp abrasion, superficial lateration face: nose fracture
2	moderate	Skin: major avulsion Vault fracture: simple, undisplaced Mandible fracture: open, displaced Maxilla fracture: LeFort I and II
3	serious	Basilar fracture Maxilla fracture: LeFort III Total scalp loss, single contusion cerebellum
4	severe	Vault fracture: complex, open with torn, exposed or loss of brain tissue, small epidural or subdural hematoma
5	critical	Major penetrating injury (>2 cm) Brain stem compression, large epidural or subdural hematoma, diffuse axonal injury (DAI)
6	survival not sure	Massive destruction of both cranium and brain (crush injury)

2.3.3.4 Head Impact Power (HIP)

According to Newman et al. (2000: 363), the HIP is based on "the general rate of change of translational and rotational kinetic energy for any rigid object", which is in the following form:

$$\text{Power} = P = \sum m.a\ .\bar{v} + \sum I\alpha.\bar{\omega} \tag{2.7}$$

where:

$a =$ linear acceleration (m/s^2)

$\bar{v}$ = linear velocity (m/s)

I = mass moment of inertia (Nms^{-2})

m = mass (kg)

$\bar{\alpha}$ = angular acceleration (rad/s^2)

$\bar{\omega}$ = angular velocity (m/s)

Then, "when the coefficients are set equal to the mass and appropriate mass moments of inertia for the human head" (Newman et. al. 2000: 363), the expression is:

$$HIP = C_1 a_x \underbrace{\int a_x dt + C_2 a_y \int a_y dt + C_3 a_z \int a_z dt}_{\text{Linear contribution}}$$

$$+ \underbrace{C_4 \alpha_x \int \alpha_x dt + C_5 \alpha_y \int \alpha_y dt + C_6 \alpha_z \int \alpha_z dt}_{\text{Angular contribution}} \qquad (2.8)$$

where:

C_i = coefficient are set as the mass and appropriate moments of inertia for the human head (50th percentile): $C_1 = C_2 = C_3$= 4.5kg, C_4 = 0.016 Nms^{-2}, C_5 = 0.024 Nms^{-2}, C_6 = 0.022 Nms^{-2}

a_x, a_y and a_z ($m\ s^{-2}$) = the linear acceleration components along the three axes of the inertia reference space attached to the dummy head.

α_x α_y and α_z ($rad\ s^{-2}$) = the angular acceleration component around the three axes of the inertia reference space attached to the dummy head.

Figure 2.6 shows the probability of concussion based on HIP_m from Newman et. al. (2000).

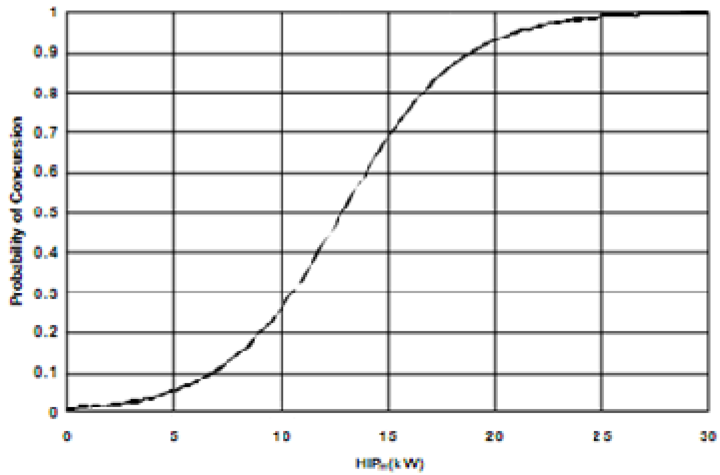


Figure 2.7: Probability of concussion based on HIP_m

(Source: Newman et. al., 2000: 365)

Furthermore, looking back at Marjoux et al. (2007), the HIP for the football player cases was found to start from 3 kW to 57 kW (see Figure 2.8), motorcyclist cases from 6 kW to 132 kW and pedestrian cases from 15 kW to 142 kW.

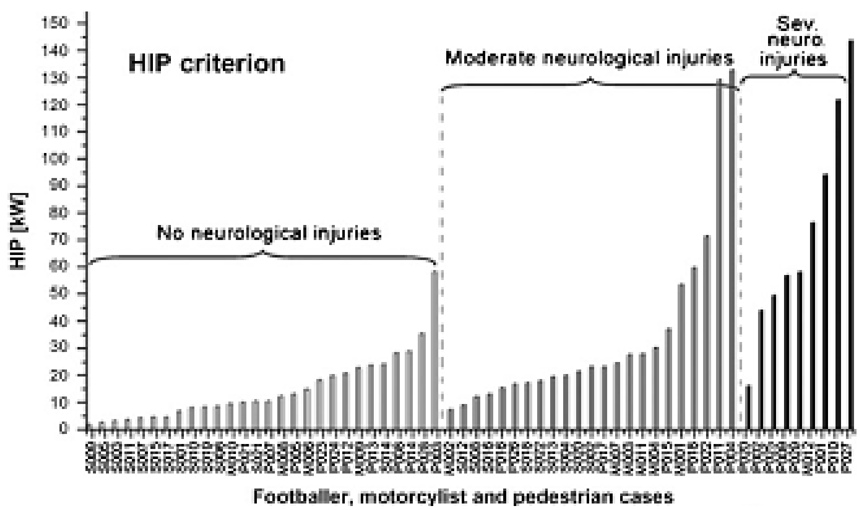


Figure 2.8: Histogram of Head Impact Power on footballer, motorcylist and pedestrian cases (Marjoux et al., 2007: 1139)

A recent study on brain deformation under mild impact by using a finite element method has been conducted by Chen et. al. (2012). The vivo human brain deformation under mild impact was induced by a 2 cm head drop by using tagged MRI and the harmonic phase (HARP) imaging analysis technique which was initially developed for cardiac motion analysis. Further FE simulation of mild impact was carried out using a patient-specific 3-D head model. A worthy correlation was found between the FE modeling and the MRI-based assessment results. The study discovered that the maximum deformations occurred within a few milliseconds after the impact during the first oscillation of the brain within the skull. Here, the maximum displacements were 2-3 mm and the maximum strains were 5-10%. Figure 2.7 presents the displacement time history of node on the brain close to the impact site obtained from FE simulation from the study by Chen et. al. (2012).

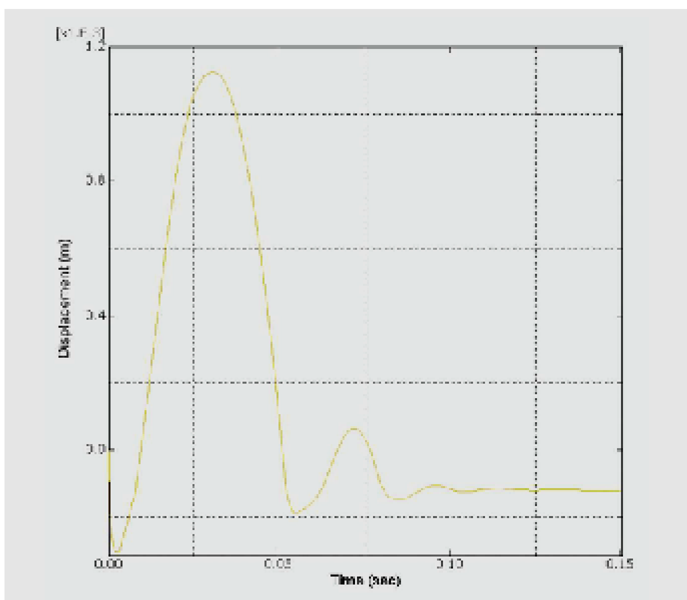


Figure 2.9: Displacement time history of node on the brain close to the impact site obtained from FE simulation

(Source: Chen et. al., 2012: 29)

According Daniel Price, (2007), study in soccer ball, this study showed that impact velocity (Figure 2.10) had a profound effect on the measurements of dynamic force and deformation. It should be noted that the 30 m/s force data, gave significant variability due to natural frequency limitations of the force plate. The FE model showed good agreement with experimentation which gave confidence in its efficacy in understanding soccer ball impacts and its use to assist in the development of future soccer ball designs. Base on Federation International Football Association the weight of football is 420 to 445 gram for outdoor football. In Figure 2.10 describe the speed 9 m/s with the impact force is 1494 N and 14 m/s with the impact force 2750 N and 23 m/s with impact force 4300 N and 30 m/s with impact force 6942 N.

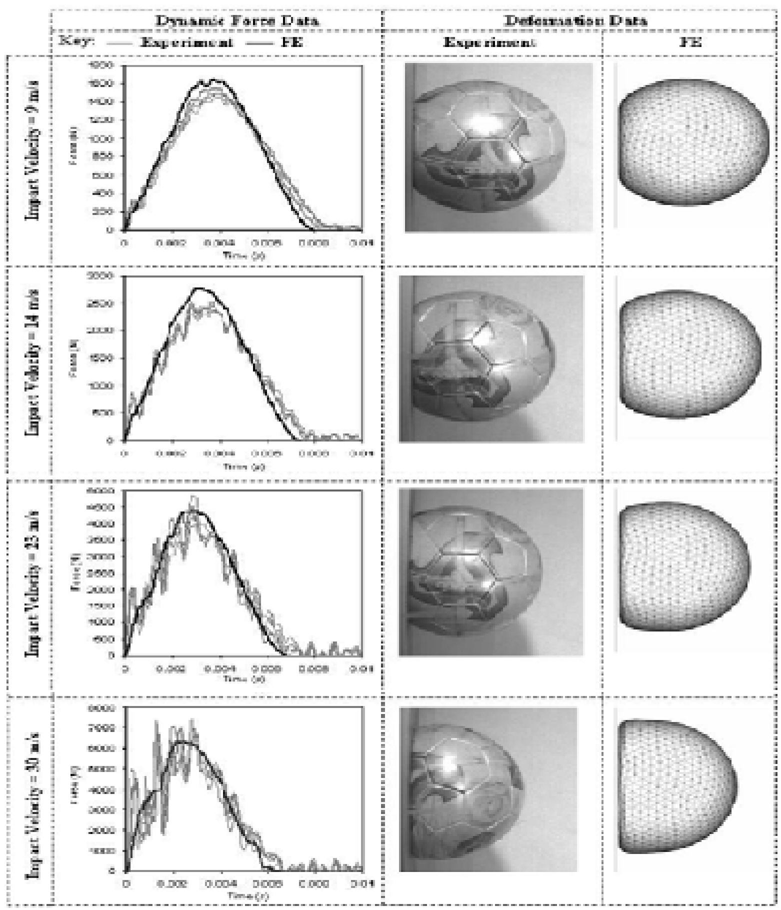


Figure 2.10: Experimentation and FE model comparisons of force vs time, and deformation data for impact velocities of 9 m/s, 14 m/s, 23 m/s and 30 m/s respectively. (Source: Daniel Price, 2007)

2.4 Human Motion

Head injuries are significantly affected by human motion parameters. Therefore, in assessing head injuries, it is also essential to study the human motion. Durward et. al. (1999) mentioned the key mechanical variables in movement analysis are time, linear displacement, linear velocity, linear acceleration, angular displacement, angular velocity, angular acceleration, force and moment. In relation to the movement of the brain, the present study also measured and reported these techniques of measurements.

2.4.1 Parameter Measurement of Human Motion

Phillips (2000) stated that for the kinematics motion in the human body, there are two types of analyses which can be studied, namely: linear and angular. Both of these motions are elaborated in the following subsections.

2.4.1.1 Linear Kinematics

Phillips (2000) explained that linear kinematics is the understanding of the human body in a dynamic state. Kinematics analysis involves the relationship between positions, with its first derivative (velocity) and its second derivative (acceleration). These positions include vector quantities, thus for uniaxial motion, a coordinate axis (such as *x)* is defined along which the movement occurs. The applicable kinematic parameters are then defined in that course.

Uniaxial linear movement (or translation) is a motion occurring along a straight line. There are many conditions where the motion of objects is only in one direction. An example from Phillips (2000) is that of a car being driven on a straight road as it moves upward along a uniformly inclined hill. Another example is of a skier moving along a straight course as the person proceeds down a uniformly declined hill.

2.4.1.2 Angular Kinematics

Phillips (2000) explained that the kinematic equations for rotational movements would include angular position and displacement, angular velocity, and angular acceleration. In view of circular motion, the velocity and acceleration vectors are two orthogonal directions to the circular path. One direction is normal *(n)* and the other tangential *(t)* to the circular path.

The velocity vector (v) is measured as a digression to the course of the body's motion and is selected as the tangential or linear velocity. The rate of change of the relative position of the body along a segment *(s)* of the circular path is the magnitude of the linear velocity:

$$v = \frac{\Delta s}{\Delta t} \tag{2.9}$$

The acceleration vector has two orthogonal (tangential and normal) components for circular motion. The rate of change of the linear velocity vector is the tangential acceleration:

$$a_t = \frac{dv}{dt} \tag{2.10}$$

The normal acceleration, a_n, is the rate of change in the direction of the velocity vector:

$$a_n = \frac{u^2}{r} \tag{2.11}$$

Since $s = r.\,\theta$, and for a circular motion the radius *(r)* is a constant, then Equation (2.4.1) can be redefined as:

$$v = \frac{d(r\theta)}{dt} = r\frac{d\theta}{dt} \tag{2.12}$$

As the rate of change of angular displacement is the angular velocity, therefore:

$$v = r.\omega \qquad (2.13)$$

By substituting Equation (2.4.5) into Equation (2.4.2), we can define the tangential acceleration for motion in a circular path in terms of the angular velocity:

$$a_t = \frac{d}{dt}(r\omega) = r\frac{d\omega}{dt} \qquad (2.14)$$

Thus the rate of change of the angular velocity is the angular acceleration:

$$a_t = r.\alpha \qquad (2.15)$$

The outcome from substituting Equation (2.4.5) into Equation (2.4.3) is:

$$a_n = r.\omega^2 \qquad (2.16)$$

The implication of Equations (2.13), (2.15), and (2.16) is that they relate the linear parameters (v, a_t, and a_n) to the angular parameters (r, θ, and α).

2.4.1.3 Force and Moment

Newton (1687) explained the Newton's second law as: "when an unbalanced force acts on a body it produces an acceleration which is proportional to the force and in aversely proportional to the inertia of the body, and is in the direction of the force".

This is often simplified to:

force = mass x acceleration

$f = m.a$ (where the force and acceleration are in same direction)

Then, $v = u + a.t$

$$a = \frac{(v-u)}{t}$$

hence $f = m.\frac{(v-u)}{t}$ or $f.t = m.v - m.u$ (2.17)

Newton's second law for angular of the impulse/momentum is:

$$T = I.\alpha$$

But $\omega_f = \omega_i + \alpha.t$ or $\alpha = \frac{(\omega_f - \omega_i)}{t}$ (2.18)

hence $T = I\frac{(\omega_f - \omega_i)}{t}$ or $T.t = I.\omega_f - I\omega_i$ (2.19)

where:

T is the moment (or torque) applied to the object

t is the time taken for the change in orientation to occur

I is the moment of inertia of the object around the axis of rotation

α is the angular acceleration of the object

ω_f is final angular velocity of the object

ω_i is initial angular velocity of the object

2.4.2 Three-Dimension of Photogrammetric Method

Photogrammetric methods are often used in occupational biomechanics. One camera can be used when a motion is performed in one plane, while for three-dimensional analysis two or more cameras are usually required. Martin and Pongratz (1974) mentioned that photogrammetric method uses the three-dimensional reference system to capture images (see Figure 2.11).

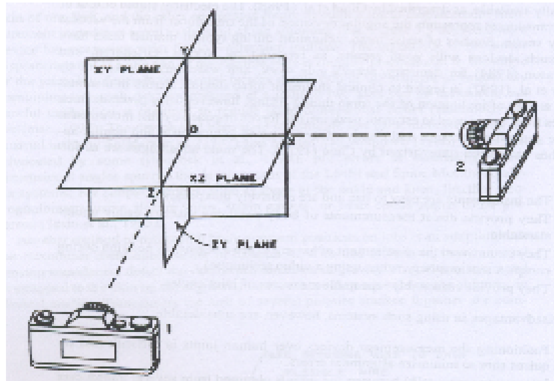


Figure 2.11: Three-dimensional reference systems.

(Source: Martin & Pongratz, 1974: 470)

The formula below depicts an orthogonal arrangement for two cameras. When the cameras are positioned with perpendicular optical axes, accurate three-dimensional point position in space can be obtained using the following formula (Martin and Pongratz, 1974).

$$x = \frac{XYx\left(1 - \frac{ZYz}{DZ}\right)}{1 - \frac{(XYz)(ZYz)}{(Dz)(Dx)}} \qquad (2.20)$$

$$y = ZYy\left(1 - \frac{x}{Dx}\right) \qquad (2.21)$$

$$z - ZYz\left(1 - \frac{x}{Dx}\right) \qquad (2.22)$$

Where:

x,y,z are the actual values of coordinate of a given point in space

XYx is the x-coordinate measured in the *XY* film plane

ZY*y* is the y-coordinate measured in the *ZY* film plane

ZYz is the z-coordinate measured in the *ZY* film plane

Dx is the distance from film plane 2 to the origin along the *x*-axis

Dz is the distance from film plane 1 to the origin along the z-axis

However, Chaffin et. al. (1999) commented that the techniques above assumed the use of optically perfect cameras. Since optical distortion exists, various techniques have been used to reduce errors from those sources. Another requirement of the photogrammetric system is its ability to precisely locate a moving target. This can be achieved by using a strobe light set close to the optical axes of the cameras. Reflective markers are taped either directly over the joint centres on the skin or on tight-fitting clothing. This results in a set of separate point film frame that can join to form a linkage movement diagram.

2.5 Summary

From the literature review, it can be concluded that most studies on injuries in sports reported that the prevalence of head injuries experienced by players is specifically mild concussion which is categorized in the mild trauma brain injury (MTBI).

The general head injury assessments comprise of Head Injury Criterion (HIC), Abbreviated Injury Scale (AIS) and Head Impact Power (HIP). The equation for HIC, shown in Equation 2.2, calculates the contact time and resultant of acceleration on the center of gravity of the brain. The AIS provides the level of injury, which is categorized and subdivided into 6 levels: minor, moderate, serious, severe, critical, and survival not sure (fatal). The HIP is derived from the linear and rotational acceleration of the head during impact and on impact duration.

Head injuries are essentially influenced by parameters of the human motion. To further assess head injuries, the key mechanical variables in movement analysis such as time, linear displacement, linear velocity, linear acceleration, angular displacement, angular velocity, angular acceleration, force and moment are important parameters to be measured.

METHODOLOGY

3.1 Introduction

This chapter provides a detailed discussion on the research framework implemented in this study. It also presents the process of data analysis and the validation methods used.

3.2 The Research Framework

This research is divided into six phases. An overview of the entire research framework is outlined in Figure 3.1. The first phase is a review of the literature as outlined in Figure 3.2 and presented in CHAPTER 2. The subsequent five phases includes survey (questionnaire) and anthropometric measurements of the subjects (outlined in Figure 3.3), analysis of the game recordings of the Sepak Takraw championships in Malaysia from 2009-2011, drop test experiments, finite element analysis and the validation of computational results with experimental methods.

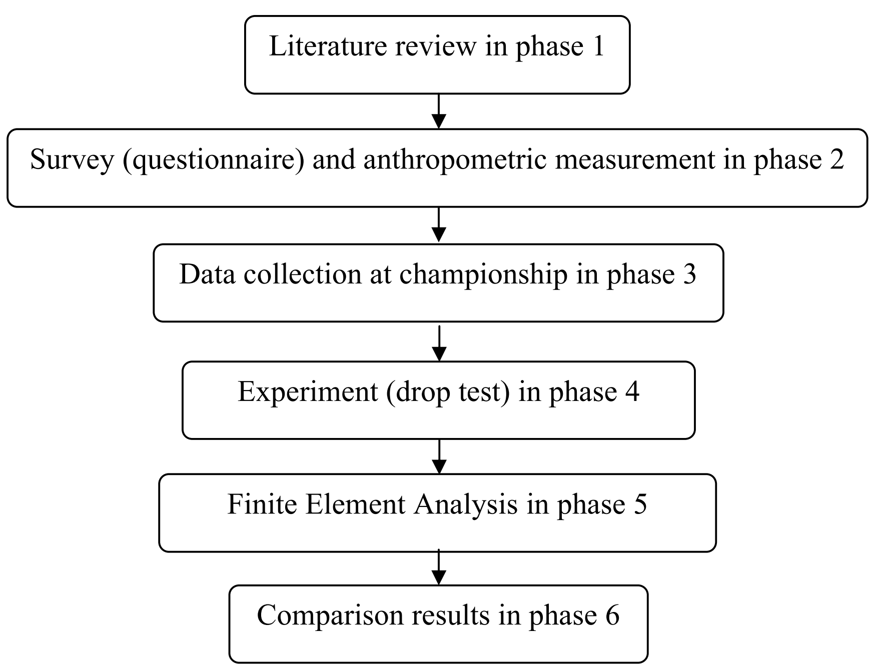


Figure 3.1**:** Overview of research framework

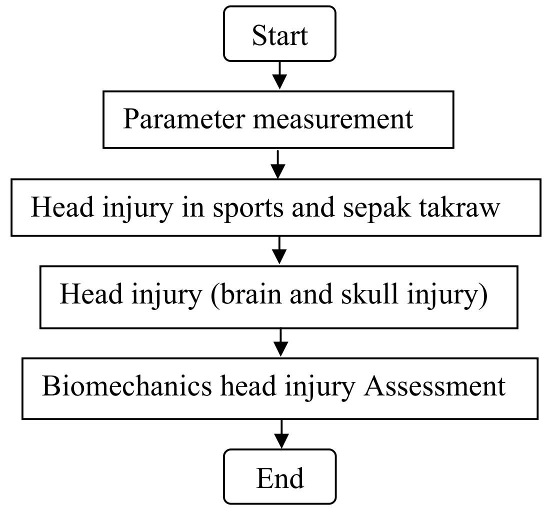


Figure 3.2**:** Phase 1 for the study of literature

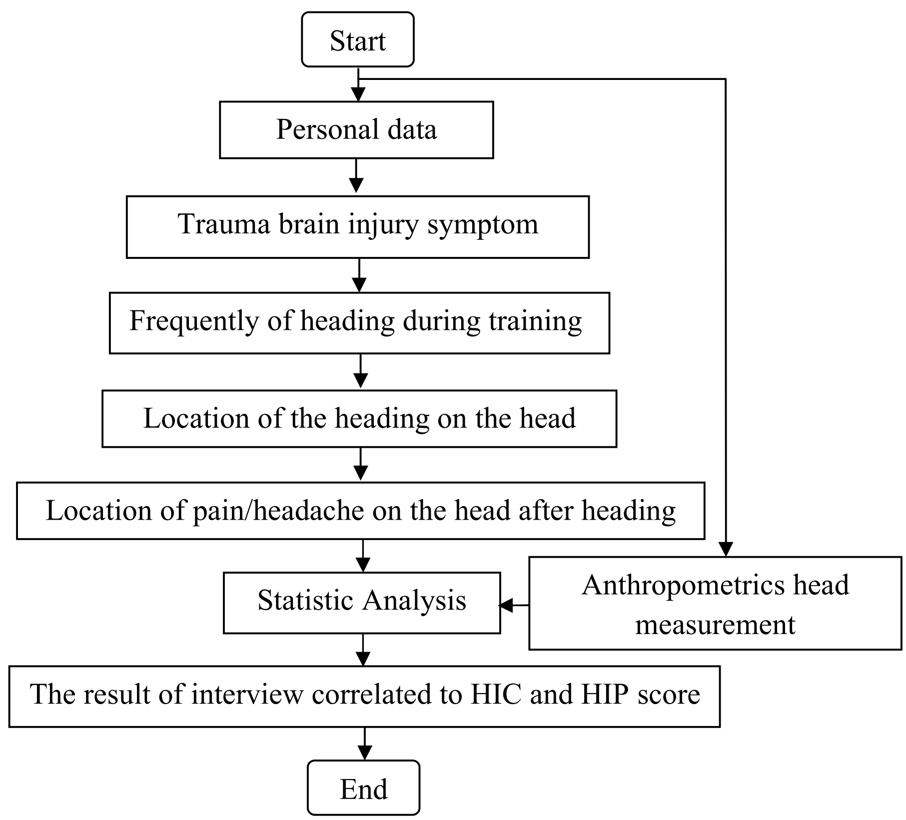


Figure 3.3**:** Phase 2 is the interview (questionnaire) and anthropometrics data

Figure 3.4 shows the steps taken in the third phase of this research, which was collecting data from Sepak Takraw championship events. This included the collection of data from high speed video recordings to measure the speed of sepak takraw ball before and after headings from the first services in the games. Afterwards, the contact time and positions of heading on the head were calculated.

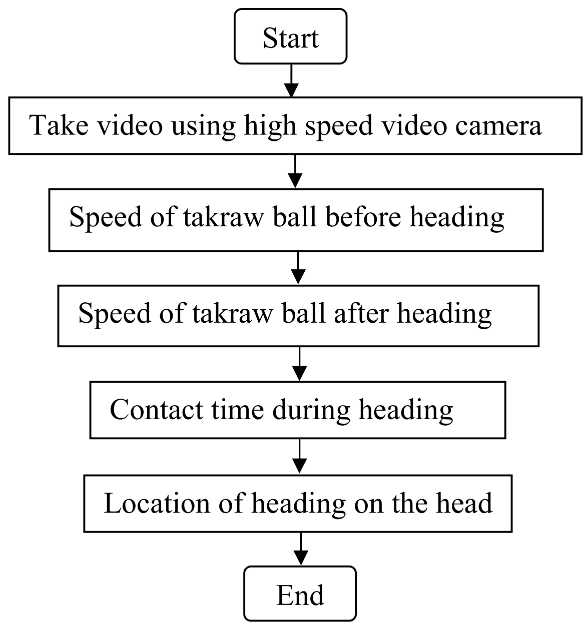


Figure 3.4**:** Phase 3 is the data collection at championships

The fourth phase was the drop test experiment on the skull dummy. This step would also cover the editing of 3D CAD skull data to reduce computational complexity and to ease the rapid prototyping process. Irrelevant parts of the skull, namely some parts on the nose, gums, teeth, and jaw were removed using CATIA software. The process involved in this phase is shown in Figure 3.5.

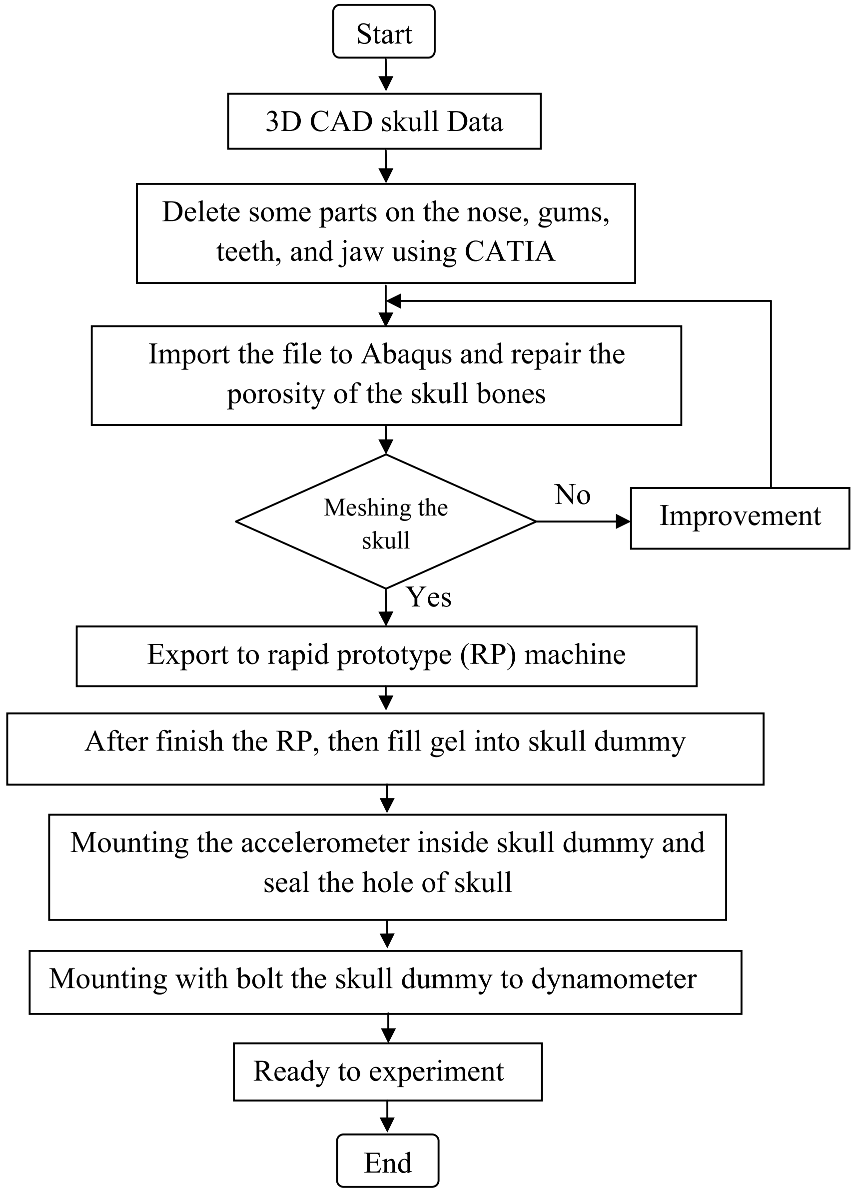


Figure 3.5**:** Phase 4: experiment of drop test heading

The fifth phase comprised of the ball heading simulations by using finite element method in Abaqus/CAE software, finite element CAD model of human scalp, skull, CSF and brain. The procedures to digitally model the human head and subsequent finite element analysis are shown in Figure 3.6.

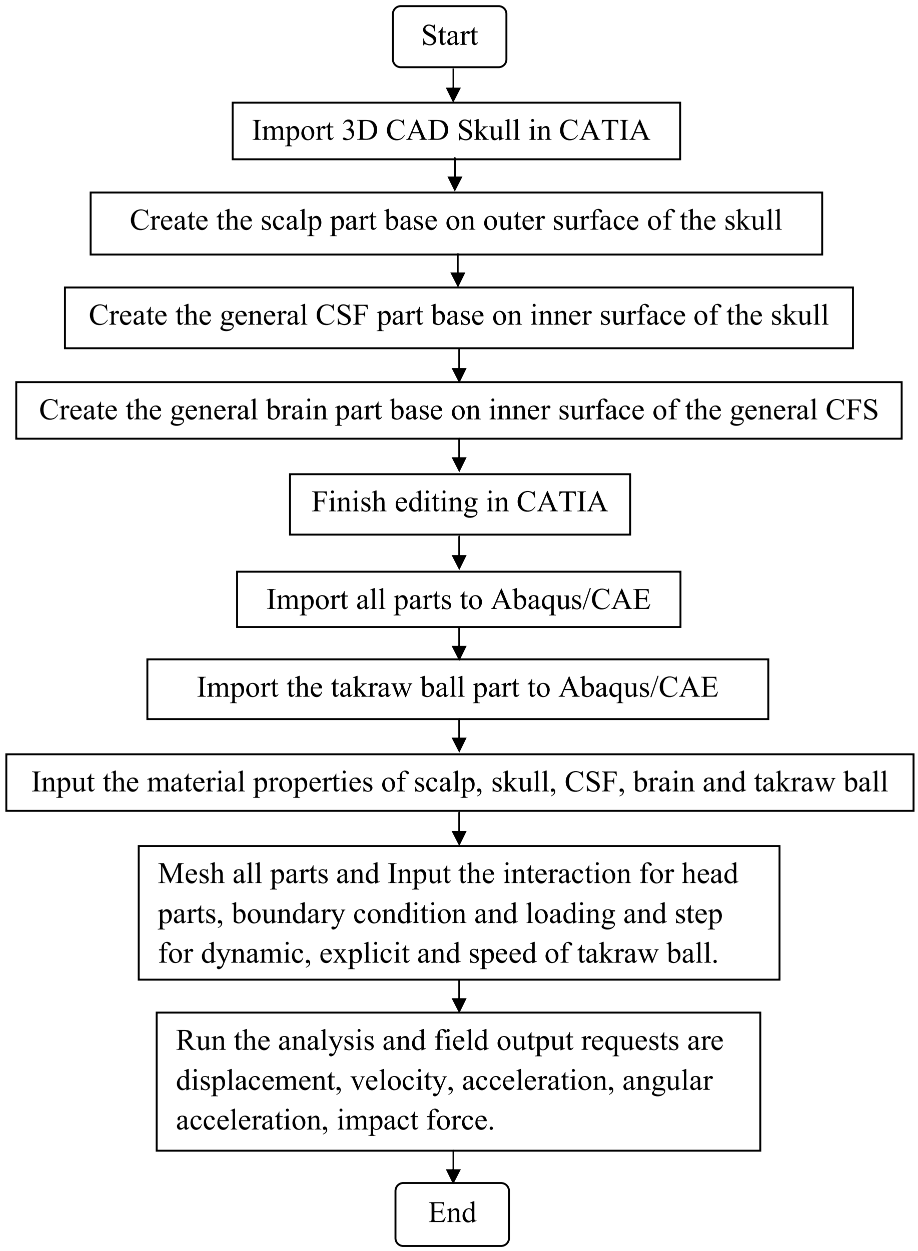


Figure 3.6**:** Phase 5: Finite element analysis of the heading

Figure 3.7 shows the work flow of phase six comparing experimental and analytical results. This phase consists of the comparison of sepak takraw ball speed before and after headings, contact times for the drop-test heading, front-forehead heading, top-forehead heading and side-forehead heading. The accelerations from the experiment on skull dummy and simulation (FEA) were also compared.

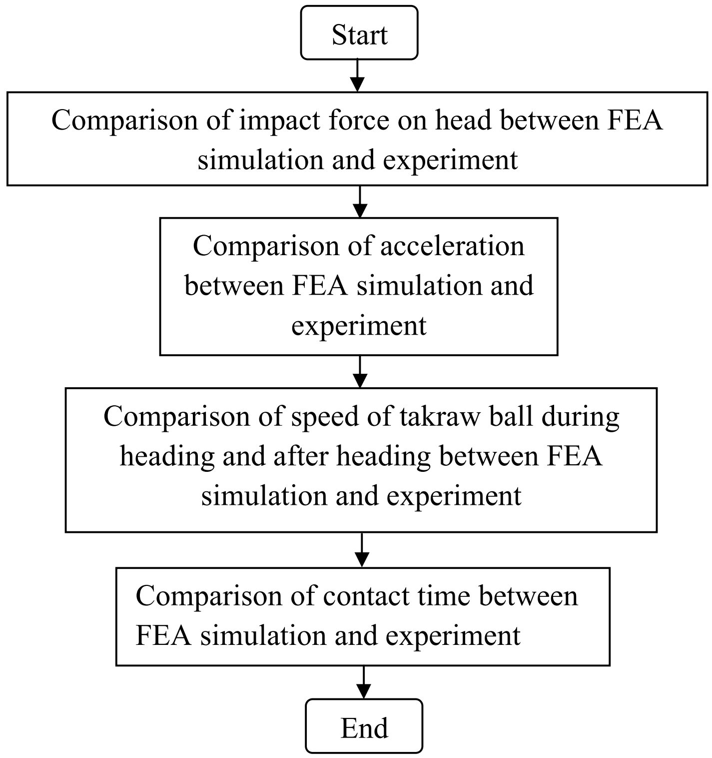


Figure 3.7**:** Phase 6: comparison results between experiment and simulation

3.3 Data collection method

A total of four main surveys were conducted. The first survey was a general interview of the players, the second survey was used to measure the anthropometric dimensions of the players' heads. The third survey was to specifically evaluate the killer headings following the first sepak takraw ball services, and lastly, the fourth survey evaluated the speed of the sepak takraw ball before and after headings.

The experimental methods consisted of experimental design, task procedure and experimental procedure. These are further elaborated in Section 3.3.2.

3.3.1 Survey

Initial observations were conducted on the Malaysian national Sepak Takraw players at the National Training Centre in Kuala Lumpur prior to data collection from interviews. The purpose of the observation was to understand the training and competition scenarios as experienced by the players. The daily training schedules were also discussed with the coach. The questionnaire (see Appendix A) was then designed based on the initial observation to identify the symptoms of possible mild trauma brain injury Ontario Neurotrauma Foundation, MTBI & persistent symptoms. (2009), Lovell et. al. (1998) and also input from experts at Institut Sukan Negara Malaysia. This questionnaire was divided into three sections, namely Section A on personal data, Section B on MTBI symptoms after headings and Section C on the heading frequency and heading positions.

A preliminary survey in the Khir Johari Championship in 2009 in Kuala Lumpur was also conducted to interview ten players with the pre-test questionnaire and also to obtain the speed of the ball from services and headings by the players. The games were recorded using a high speed video camera but with low frames, at 300 fps, because there was not enough lighting in the court. The photogrammetric method was applied (see Figure 3.9). Then, the videos were manually digitized using the motion analysis software Digiman High Speed (HS) (see Figure 3.8). The software computed the linear displacement, linear velocity, linear acceleration, angular velocity, angular acceleration and also trajectory of sepak takraw ball (see Figure 3.10).

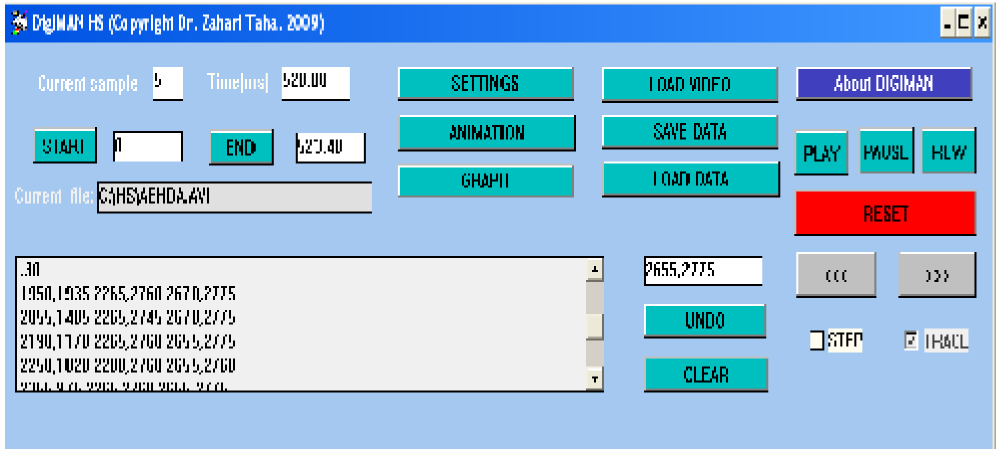


Figure 3.8: Interface Digiman HS

Figure 3.9: Recoding data from championship: front view (right) and side view (left)

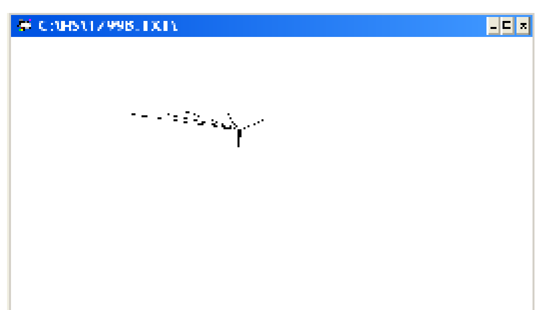


Figure 3.10: Example of trajectory of sepak takraw ball from Digiman HS

Subsequent data collection was conducted during the KFC-Utusan Sepak Takraw Championship in 2011 held in Kuala Lumpur. Players from states in Malaysian peninsula such as Selangor, Negeri Sembilan, Johor, Kedah and Pahang had participated in the event. One hundred players (or, subjects of the study), consisting of feeder, tekong and killer players, voluntarily participated in the survey interview (denoted as Survey 1). The purpose of this survey was to understand the potential occurrences of head injuries amongst them. The subjects were males of 16 years minimum age and are minimum level of skill club players.

Following the interview sessions, the anthropometric measurements of the head of the players were also collected (denoted as Survey 2). The objective of these measurements was to determine whether the existing CAD model of the head truly represented the population percentile of the Malaysian Sepak Takraw player's ten dimensions for the head anthropometric data were measured for from the one hundred subjects (Table 3.1). The measurements were performed in the standing posture in accordance to the guidelines of Gross et al. (1994), Kroemer and Kroemer (1993) and White (1995), using the anthropometer equipments as shown in Figure 3.11. The full measurement data is listed in Appendix B.

Table 3.1: Anthropometrics measurement

Dimension (mm)	
1	Weight (kg)
2	Stature
3	Head length
4	Head breadth
5	Tragion to top of head
6	Menton-sellion length (face length)
7	Bizigomatic breadth headboard
8	Interpupillary breadth
9	Head circumference
10	Neck circumference

Figure 3.11: Anthropometer for measuring physical dimensions

The third session of data collection was conducted at the Sepak Takraw World Cup in 2011 in Kuala Lumpur. The purpose was to obtain the data on spike failures from killer players after killer headings during the first sepak takraw ball services (denoted as Survey 3). The results were then correlated with the players' interviews. The method of data collection for this survey was limited to only visual and manual account of the spike failures from the killer players. Video recordings could not be taken as the organizer had prohibited the use of a video camera to record the games in session. The total samples of data were collected from 18 games with 58 sets.

The final data collection session was conducted at the KFC-Utusan Sepak Takraw in 2011 in Kuala Lumpur, where video recordings were possible to be conducted. The purpose of this survey was to measure the sepak takraw ball speed before and after headings from services in the games (denoted as Survey 4). The data for speed was subsequently used for the FE simulation of the ball heading model. Similarly, the contact times of headings were also measured. A comparison between FE simulations and the actual measurements could then be made. A summary of the four surveys conducted, their sample numbers and objectives are provided in Table 3.2.

Table 3.2: List of survey conducted in this research

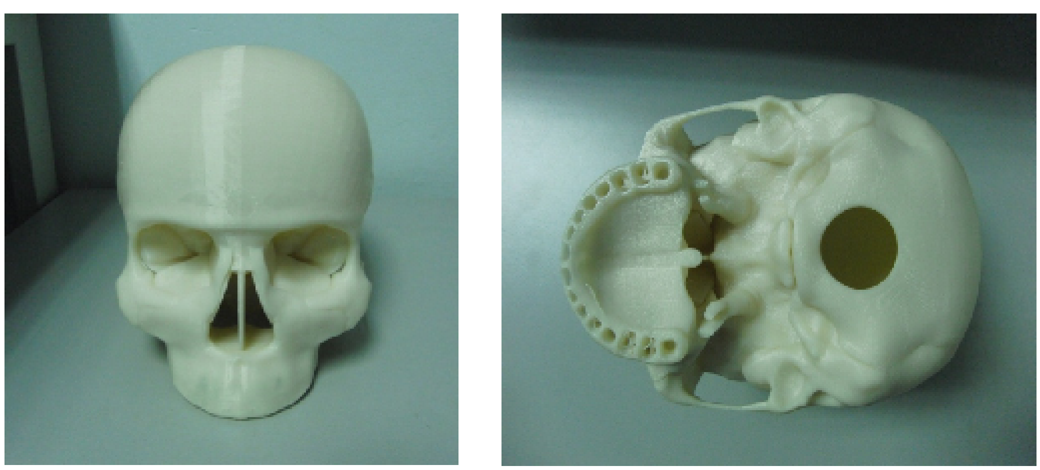
Survey	Samples (Player)	Parameter	Analysis and method (reference)
Survey 1 Purpose: interview was conducted to understand potential occurrences of head injuries among professional player	100	MTBI symptoms Frequency of heading Positions of heading	Questions of MTBI symptoms based on Ontario Neurotrauma Foundation, MTBI & persistent symptoms. (2009) and Lovell et. al. (1998). Statistic analysis were conducted by using Cronbach alpha (DeVellis, 1991), descriptive statistic, and binomial (Santoso, 2001)
Survey 2 Purpose: measurement was conducted to obtain anthropometrics head data for comparison with 3D CAD model.	100	10 measurement of Anthropometrics head data (mm) for each subject	Percentile of the population (Gross et. al., 1994), Kroemer and Kroemer (1993)
Survey 3 Purpose: to obtain spike failure from killer players and correlate them with the results from the interview with players	18 games (58 set)	Spike failed from the killer players after heading the first ball.	Used the visual and manual account method.
Survey 4 Purpose: to obtain the sepak takraw ball speed in the championship before and after headings.	17	Speed (m/s) of sepak takraw ball before and after headings, contact time of the headings.	Measured the speed by using the phantom software and photogrammetric method (Martin and Pongratz, 1974)

3.3.2 Experimental Study

This section explains the experimental study which includes the experimental design, task procedure and experimental procedure. It is noted that this study had limited funding and limited equipments in the laboratory available. The skull dummy was made using Rapid prototype and the validation was conducted by using the FE model. The following section discusses the production of skull dummy for experiment, whilst the next section (see 3.4) presents the finite element analysis procedure.

3.3.2.1 Experimental Design

The experiment required a physical model of the human skull. Thus, the first step was the design of the human skull itself. Due to the difficulty in sourcing actual CT scan from the hospital, an existing 3D CAD design was obtained from http://humanbody3d.com, instead. The 3D skull IGS file was further edited in CATIA to repair some porosity holes in the skull bones. Once the editing process was completed, the skull was then fabricated using a rapid prototyping (RP) machine (Dimension 1200es Series), using Acrylonitrile Butadiene Styrene (P430 ABS) to produce the skull model is as shown in Figure 3.12



(a) **(b)**

Figure 3.12: Skull dummy (a) front view and (b) button view

3.3.2.2 Experimental Procedure for Drop Test of Skull Dummy

This section explains the experimental procedure for the drop test. The dummy skull is first fabricated using rapid prototyping. It is then filled with ultrasound gel and accelerometer sensors placed in the centre of gravity of the dummy skull.

The work step for setting up the sensors to the skull is shown in Figure 3.13. The following Figure 3.14 shows the work steps for setting up the high speed camera and the sepak takraw ball position to capture the images during the drop test.

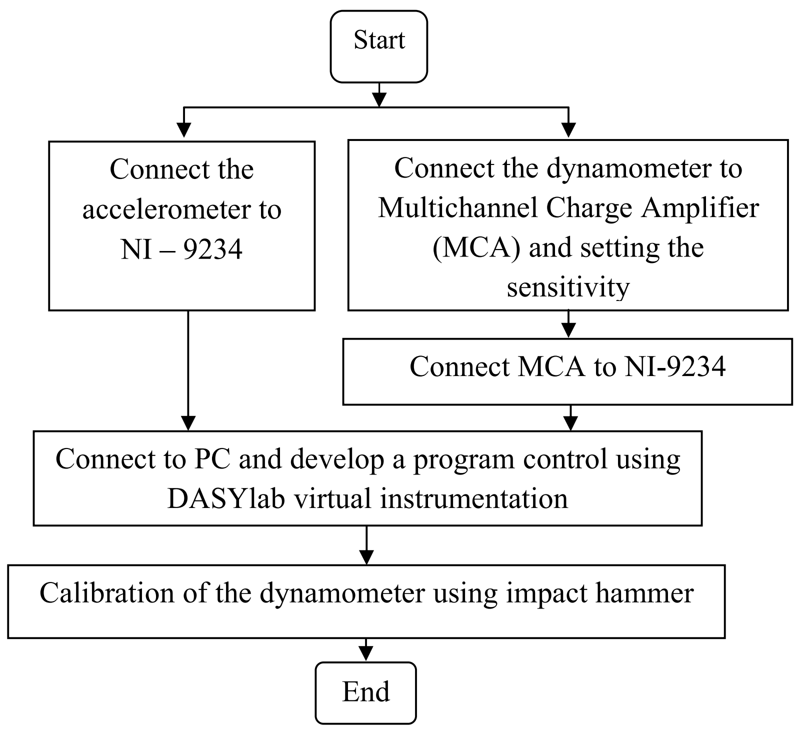


Figure 3.13: Work step of setting up the sensor

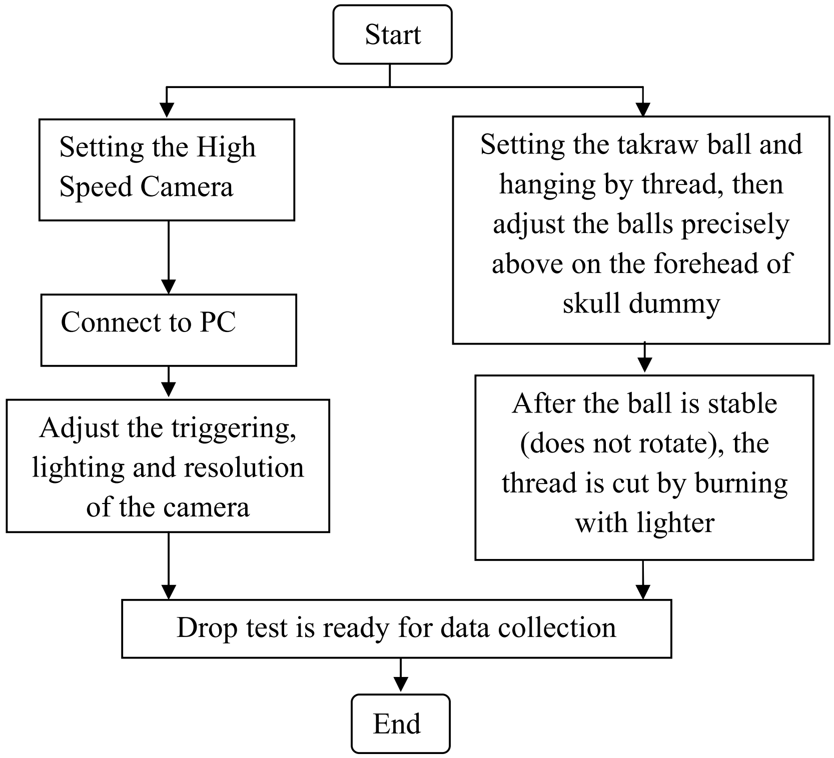
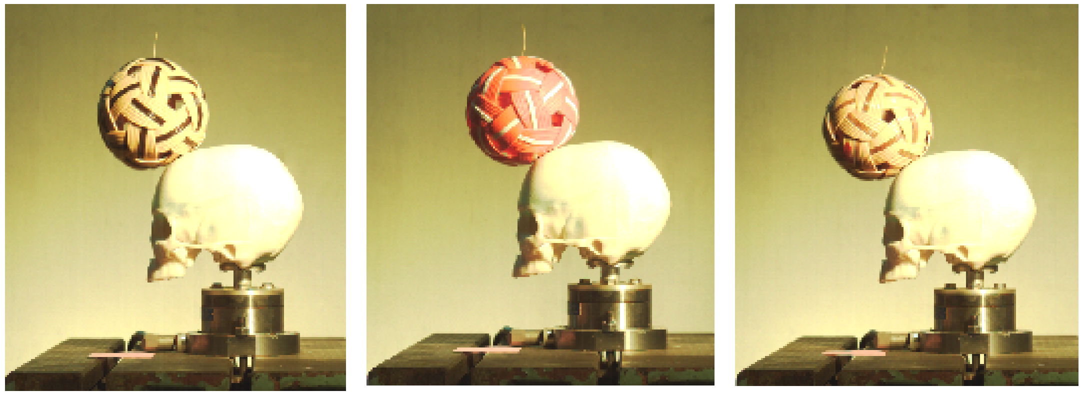


Figure 3.14: Work step of setting up high speed camera and sepak takraw ball position

Three types of sepak takraw ball brands, commonly used in international championship, were chosen for this experiment, namely Marathon, Salim and Gajah Emas. Figure 3.15 shows the three brands of sepak takraw balls during testing in the laboratory.



Marathon™ Salim™ Gajah Emas™

Figure 3.15: Three brands of sepak takraw ball in the position of heading a dummy skull in experiment

Based on the average weight of four balls for each ball type, the Marathon was found to be heavier compared to the other two brands. Table 3.3 shows that the Marathon's average weight is more than 6.081% of Salim, and 6.167% heavier than Gajah Emas. This suggests that the Marathon may exert more impact force as compared to the other two brands of sepak takraw balls for the same momentum change during collision.

Table 3.3: Weight of sepak takraw ball in gram

Marathon		Salim		Gajah Emas	
M1:	189.046	S1:	175.754	G1:	177.678
M2:	187.555	S2:	178.836	G2:	175.873
M3:	188.884	S3:	177.777	G3:	177.484
M4:	189.428	S4:	176.637	G4:	177.321
Average:	188.728		177.251		177.089

3.3.2.3 Apparatus

The main apparatus for the drop tests consists of a dynamometer, accelerometers, a phantom™ high speed camera, multichannel charge amplifier, a digital oscilloscope and a PC equipped with DasyLab data acquisition software. The

dynamometer, as shown in Figure 3.16, was used for measuring the force on the dummy skull.

Figure 3.16: Dynamometer (kistler)

The **accelerometer,** shown in Figure 3.17, was used to measure the acceleration in the brain. The accelerometer was positioned 81 mm vertically inwards from the base of the skull at the centre of gravity of the brain-gel. The skull was then carefully filled with ultrasound gel until full, as shown in Figure 3.18 and Figure 3.19, ensuring that no air traps or bubbles are formed. The eco ultrasound gel was chosen since it closely resembles the material properties of the brain fluid.

Figure 3.17: 8690C10 PiezoSmart^{TM} triaxial accelerometer

The accelerometer sensor was connected to NI-9234, and then to the computer. The set up was calibrated using an ICP impact hammer, shown in Figure 3.20, to ensure that the impact forces recorded are error-free.

Figure 3.18: EcoGel 200^{TM}

Figure 3.19: EcoGel inside the Skull dummy

Figure 3.20: ICP impact hammer and NI-9234

Figure 3.21 shows the set up of the **Phantom high speed camera** used to capture the video of the drop tests. The same camera was used in the surveys at the championship with a frame setting of 1000 fps at a resolution of 768 x 576 pixels and exposure of 990 µs.

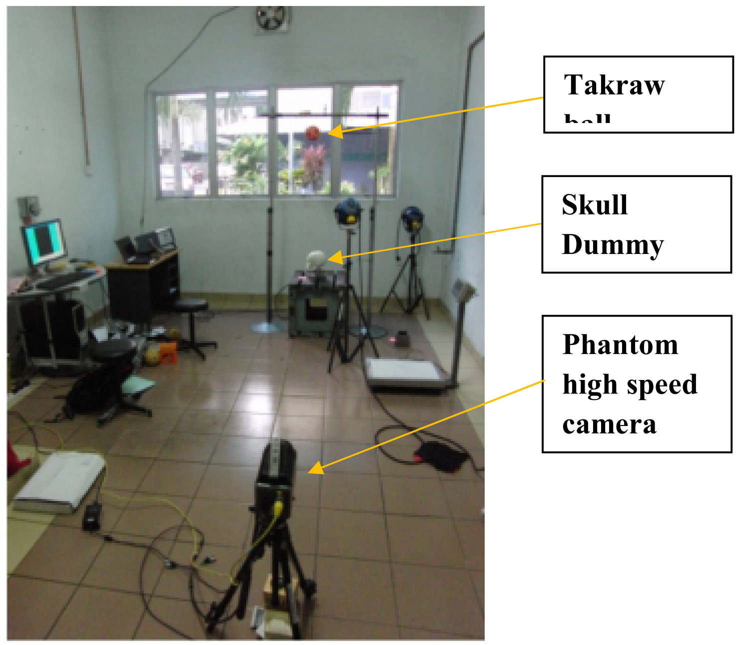


Figure 3.21: Experiment setup for drop test

The **multichannel charge amplifier** for capturing and transferring the data from the dynamometer is as shown in Figure 3.22.

Figure 3.22: Multichannel Charge Amplifier Type 5019A

The amplifier is connected to a Yokogawa oscilloscope digital DL1540, shown in Figure 3.23, to generally show the resulting signals from the measurements. It was also connected to the computer to obtain actual force data.

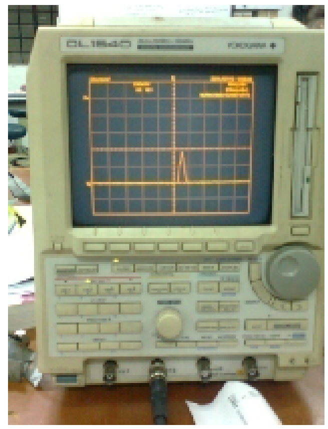


Figure 3.23: Yokogawa oscilloscope digital DL1540

An example of the result of the impact force during the experiment from the dynamometer without skull dummy was printed using Yokogawa oscilloscope digital DL1540, (Figure 3.24). The graph shows the result of a drop test of the sepak takraw ball from a 1 meter height. The impact was directly on the dynamometer without the dummy skull. This test was to ensure that the dynamometer worked properly.

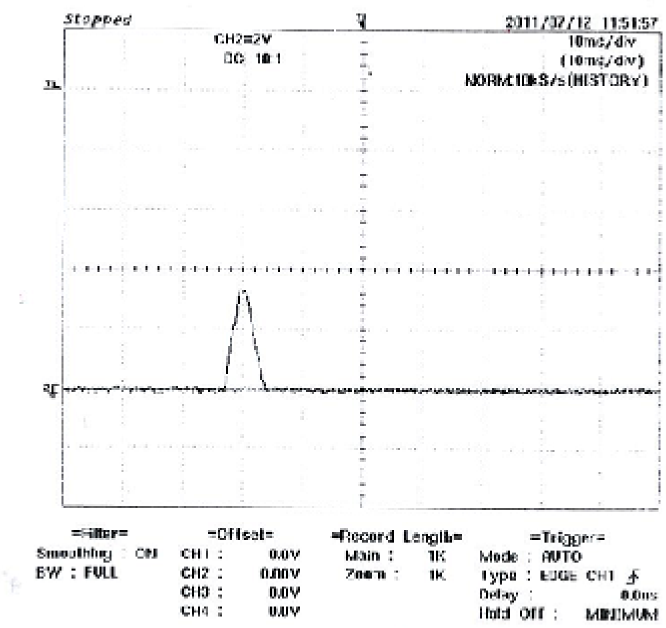


Figure 3.24: Example result of impact force from dynamometer without skull dummy and printed using Yokogawa oscilloscope digital DL1540

DasyLab software, (Figure 3.25), was also used during the drop-test experiment on the skull dummy to control and manage the data collected for accelerations, impact forces and the video recordings from the high speed camera.

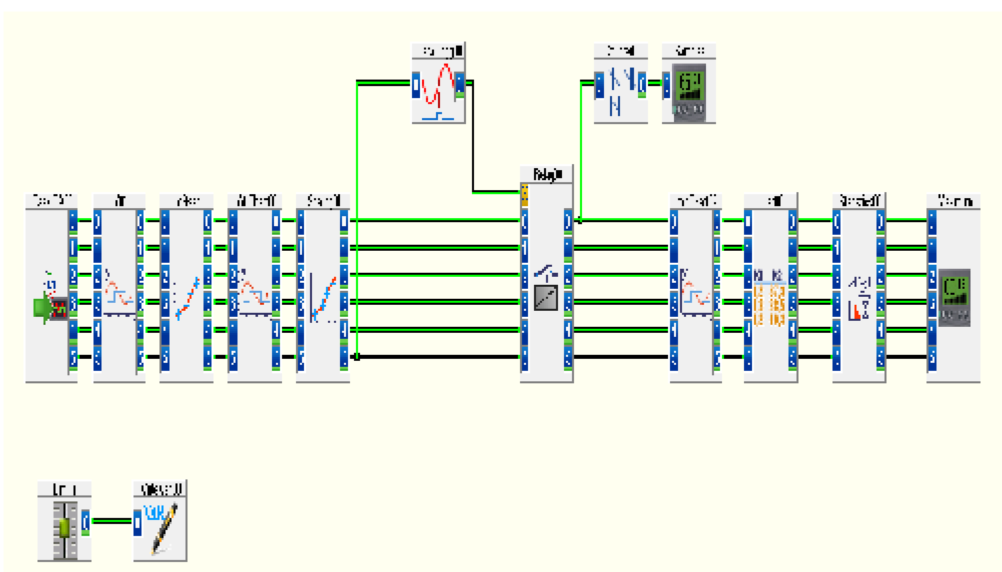


Figure 3.25: Worksheet from DasyLab for drop test measurement

In the study, the headings of the ball were measured in two conditions. The first was from the drop ball (free fall ball) experiment and the second one was from the actual games with full speed from the services (refer Figure 4.3 in CHAPTER 4). The Figure 3.26 shows the position of a ball set-up for the drop test of the sepak takraw ball. A string held the sepak takraw ball in place 1 meter from the top of the skull. To reduce the rotation of the ball, the string was cut through using a flame lighter. The high speed camera was synchronized to capture the images of the falling sepak takraw ball hitting the skull.

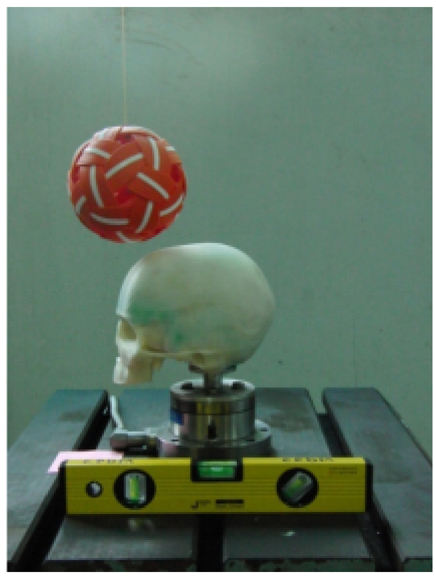


Figure 3.26: Drop test set-up position on the sepak takraw ball hanging with a thread

Figure 3.27 shows the interface of the high speed camera software used to calculate the speed of sepak takraw balls before and after the headings and the contact time of headings.

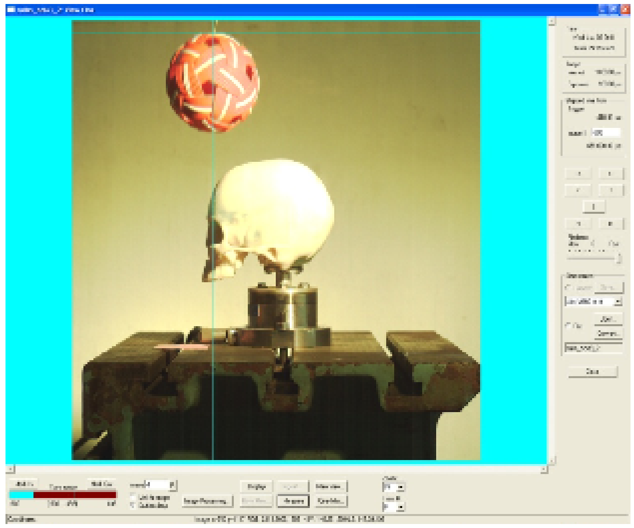


Figure 3.27: Measurement of speed using phantom camera control software

3.4 Data analysis method

This section explains the methods of analysis starting from the background theory, finite element analysis for the numerical method and validation method for the comparisons of the experiment and simulation results.

3.4.1 Finite Element Analysis Method

This section explains the material properties of the scalp, the cerebrospinal fluid, the skull and the brain and also the interactions, constraints, loads, and boundary conditions of the analysis and simulation using Abaqus/CAE 6.10-EF1 software.

3.4.1.1 Modelling Human Head and Sepak Takraw Ball Model

The skull model, shown in Figure 3.28, is retrieved from humanbody3d.com is a virtual geometry built from a CT scan and also based on the atlas anatomy. The human model is an average male with good health of about 30 years of age.

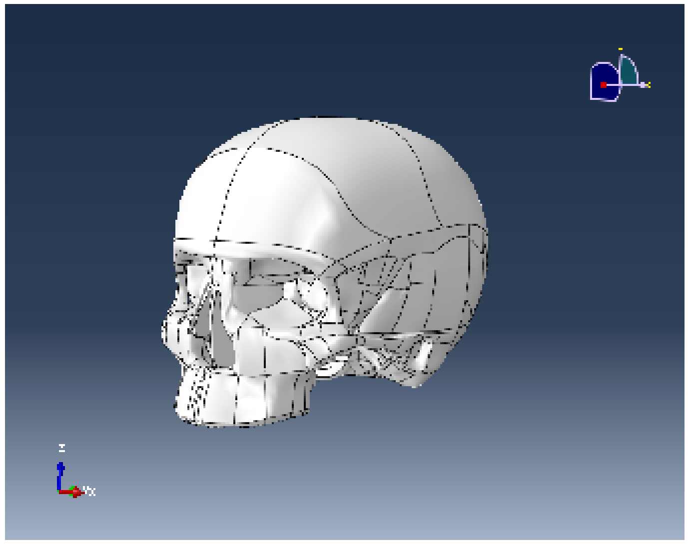


Figure 3.28: 3D cad of skull
(Source: humanbody3d.com)

The CAD model of the skull has head size measurements confirming to about 95%tile of population of the subjects in this study. Nevertheless the model was edited to reduce the size by 5.66% to get the same size of 50%tile of the Malaysian populations.

Figure 3.29 presents the position of frontal lobe point, occipital lobe point and position of accelerometer in the centre of gravity of brain mesh. The nodes were chosen to show the range of displacements in those particular positions from the ball headings simulations (see Table 3.4 and 3.5). It would also show the dislocations of the nodes after the impacts and the range of distance that does not go back to their normal positions.

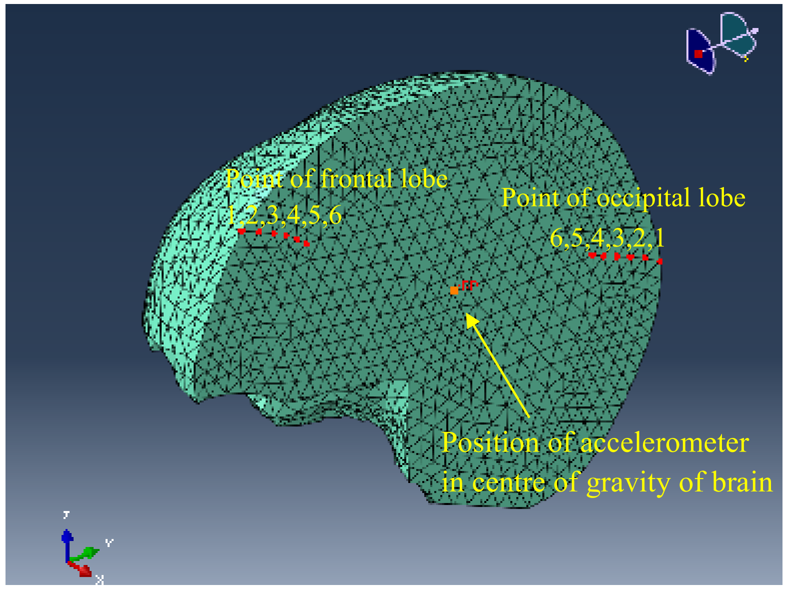


Figure 3.29: Position of frontal lobe point, occipital lobe point and position of accelerometer in centre of gravity of brain mesh

Table 3.4: Node position of frontal lobe

Point	Distance from outer brain (mm)
1	0.0
2	6.3
3	11.8
4	16.6
5	20.9
6	24.6

Table 3.5: Node position of occipital lobe

Point	Distance from outer brain (mm)
1	0.0
2	6.2
3	11.8
4	17.2
5	22.2
6	26.5

The CAD model of the sepak takraw ball, shown in Figure 3.30 is based on Ahmad et. al. (2009) having a material density of 1059.171 kg/m^3, Young's modulus of 1.0015 GPa and Poisson ratio of 0.

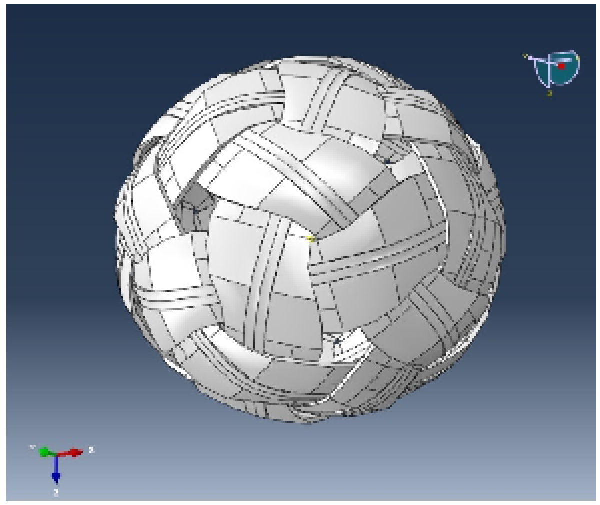


Figure 3.30: 3D CAD of sepak takraw ball

3.4.1.2 Material Properties

The linear elastic and linear viscoelastic are the material properties typically used for the brain simulation. Previous studies which have tested the material properties used for the brain simulation had provided various results. For the utilization of linear elastic, the findings are outlined in Table 3.6. Consequently, for linear viscoelastic, the findings are outlined in Table 3.7.

Table 3.6: Material properties of linear elastic brain tissue

Authors	Young's Modulus E (kPa)	Poisson's Ratio ν
Chu et al. (1994)	250	0.49
Claessens et al. (1997)	1000	0.48
Hosey & Liu (1982)	66.7	0.48
Huang et al. (1999 & 2000)	250	0.49
Khalil & Viano (1982)	66.7	0.45-0.499
Morrison III et al.(2003)	10	0.4999
Ruan et al. (1991)	66.7	0.48
Ueno et al. (1995)	80.0	0.49
Ward & Chan (1980)	66.7	0.49-0.4999
Willinger et al.(1999)	675	0.48

Table 3.7: Linear viscoelastic properties of brain material

Authors	Short-Term G_0 (kPa)	Long-Term G_∞ (kPa)	Decay Constant β (s^{-1})
Al-Bsharat et al. (1999)	33-43	6-8	500
Bandak & Eppinger (1994)	34	17	100
Cheng et al. (1990)	49	16.2	145
Gilchrist et al.(2001)	41	7.6	700
Kuijpers et al. (1995)	338	169	50-10000
Ruan et al. (1986)	528	168	35
Takhounts et al.(2003)	10.3	5	100
Willinger & Baumgartner (2003)	49	16.2	145
Zhang et al.(2001)	34-41	6.4-7.8	700

Based on the results in Table 3.6 and Table 3.7, this study has selected the material properties employed by Willingier et. al. (1999) and Willinger and Baumgartner (2003), because their findings provided the most complete set of data.

3.4.2 Linear Viscoelastic

To calculate the viscoelastic properties for the brain tissue material, Prony (1795) developed the formula shown in Equation 3.1. The relaxation for brain materials are $K(\tau)$ and $G(\tau)$ which can be defined individually in term of a series of exponentials, known as the Prony series:

$$K(\tau) = K_{\infty} + \sum_{i=1}^{nK} K_{ie}^{-\frac{\tau}{\tau_i^K}} \tag{3.1}$$

$$G(\tau) = G_{\infty} + \sum_{i=1}^{nG} G_{ie}^{\frac{\tau}{\tau_i^G}} \tag{3.2}$$

where:

K_{∞} = the long-term bulk modulus

G_{∞} = the shear modulus

In general, the relaxation times of τ_i^K and τ_i^G do not require to be equal to each other, however the Abaqus/CAE system assumes that $\tau_i = \tau_i^K = \tau_i^G$. Similarly, the number of terms in bulk and shear nK and nG, need not be equal to each other. In fact, in many practical cases it can be assumed that $nK = 0$. For this study, the selected material properties of the brain tissue are shown in Table 3.8.

Table 3.8: Selected of material properties of brain tissue

(Source: Willinger and Baumgartner (2003); Arbogast and Margulies (1999))

Parameter	Value
Young's modulus (kPa)	675
Density (kg/m^3)	1040
Poisson's ratio	0.49
Shear modulus (kPa)	226.51
Short-Term G_0 (kPa)	49
Long-Term G_∞ (kPa)	16.2
Bulk modulus (kPa)	2190000
Decay Constant β (s^{-1})	145
Prony series, base on Arbogast and Margulies (1999) g k τ	 0.895231 0 0.0103

In addition to the material properties of the brain tissues, other required material properties for the simulation model such as for the scalp, skull, CSF and sepak takraw ball were also considered, as shown in Table 3.9.

Table 3.9: Selected properties for in this study

(Source: Willinger et.al. (1995))

Part model	Young's modulus (kPa)	Density (kg/m^3)	Poisson's ratio
Scalp	16700	1130	0.42
Skull	15000000	2000	0.22
Cerebrospinal fluid	12	1040	0.49
Sepak takraw ball	1001500	1056.171	0

For drop-test simulation, the skull was made out of Acrylonitrile Butadiene Styrene (ABS) and an ultrasound-gel was used to simulate the brain with the following properties shown in Table 3.10.

Table 3.10: ABS and ultrasound-gel properties for the skull and brain

(Source: Dimensionprinting.com and Eco-Med Pharmaceutical Inc.)

Part	Density (kg/m^3)	Young's Modulus (kPa)	Poisson's ratio
Skull (ABS)	1040	2272000	0.401
Brain (gel)	1030	14.436	0.43

3.4.2.1 Moment Inertia of Brain

Various researchers have measured and determined the principal moments of inertia of the human head. The moment of inertia of the human brain can be approximately calculated by assuming the brain has the simple geometry of one half an ellipsoids or a full ellipsoid. The findings of selected researchers are shown in Table 3.11.

Table 3.11: Principle moments of inertia of the human head in the literature

Moment of Inertia ($kg.m/s^2$)	Becker et al. (1972)	Chandler et al. (1975)	McConville et al.(1980)	Zatsiorsky & Seluyanov[a] (1983)
I_{xx}	0.0199	0.0174	0.0204	0.0271
I_{yy}	0.0221	0.0164	0.0233	0.0293
I_{zz}	0.0134	0.0203	0.0151	0.0201

[a]Calculated for a person having 73 kg weight and 174 cm height.

In this study, the results for the moment inertia based on FE model were I_{xx}: 0.00361 $kg.m/s^2$ (0.035 Nms^{-2}), I_{yy}: 0.00286 $kg.m/s^2$ (0.028 Nms^{-2}) and I_{zz}: 0.00381 $kg.m/s^2$ (0.037 Nms^{-2}).

3.4.2.2 Assembly of Heading for Sepak Takraw Ball Position Parts

This section presents the assembly of the parts of models consisting of the sepak takraw ball, scalp, skull, CSF and brain. Figure 3.31 illustrates the assembly of drop-test at forehead heading in FE simulation based on the dropt test experiment. The results are presented in CHAPTER 5.

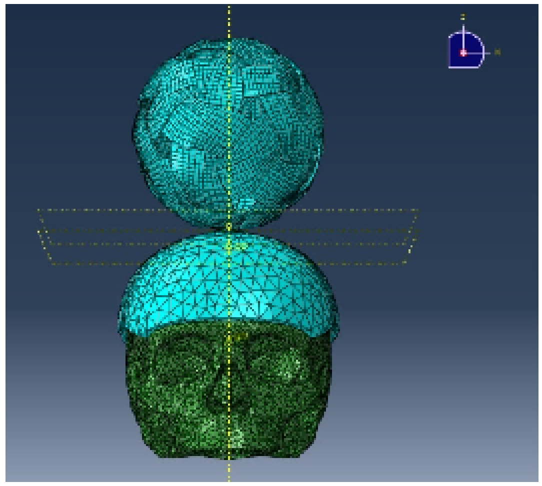


Figure 3.31: Assembly of drop-test at forehead heading FE simulation

Figure 3.32 shows the assembly of front-forehead heading in FE simulation. The configuration is based on heading no 17 captured in the KFC-Utusan championship (refer to CHAPTER 4, Section 4.5, and Table 4.37).

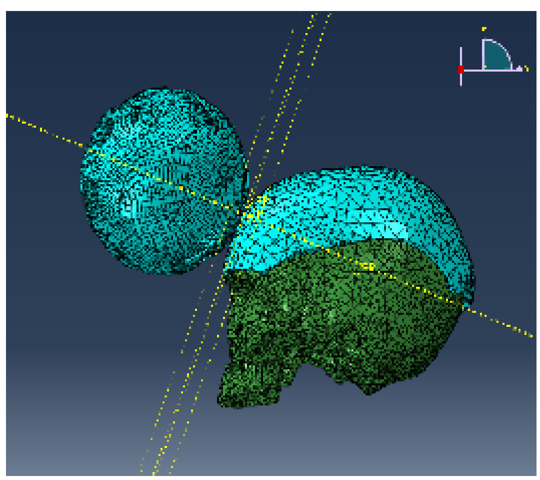


Figure 3.32: Assembly of front-forehead heading FE simulation

Figure 3.33 shows the assembly of top-forehead heading in FE simulation based on heading 15 captured in the KFC-Utusan championship (refer to CHAPTER 4, Section 4.5, and Table 4.37).

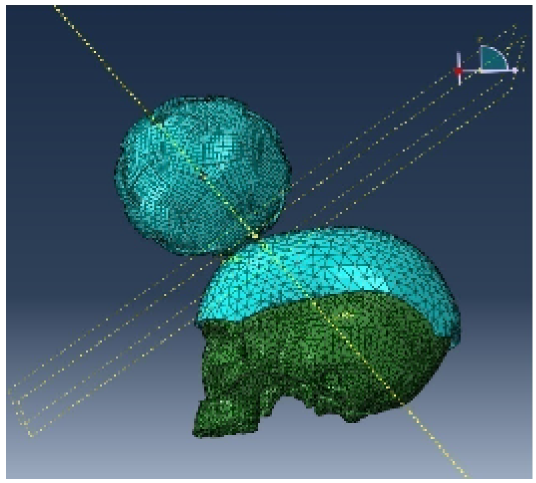


Figure 3.33: Assembly of top-forehead heading FE simulation

Figure 3.34 shows the assembly of side-forehead heading in FE simulation based on heading 10 captured in the KFC-Utusan championship (refer to the next CHAPTER 4, Section 4.5, Table 4.37).

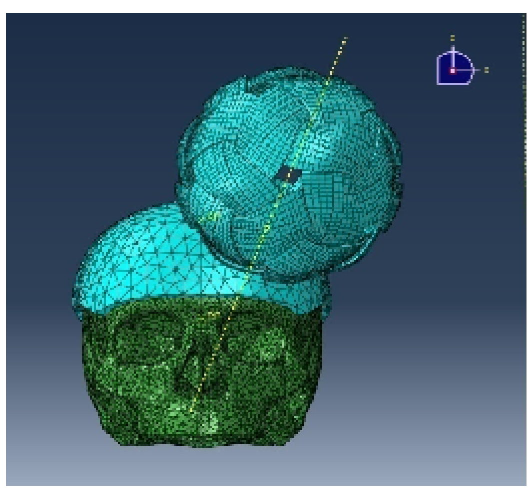


Figure 3.34: Assembly of side-forehead heading FE simulation

Figure 3.35 is the assembly of drop-test at the skull dummy using FE simulation. This test was applied for comparisons between the FE simulation and experiments in the laboratory. The results are presented in CHAPTER 6.

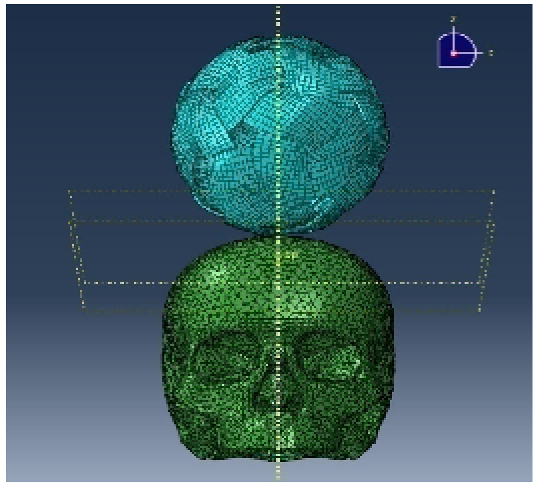


Figure 3.35: Assembly of drop-test at the skull dummy using FE simulation

3.4.2.3 Meshing of the Head and Sepak Takraw Ball Model

This section explains the head model consisting of the top of scalp, general CSF, skull, general brain.

Figure 3.36 shows the mesh of the top scalp made of 1473 nodes and 4479 elements. The element type chosen was linear tetrahedral (C3D4).

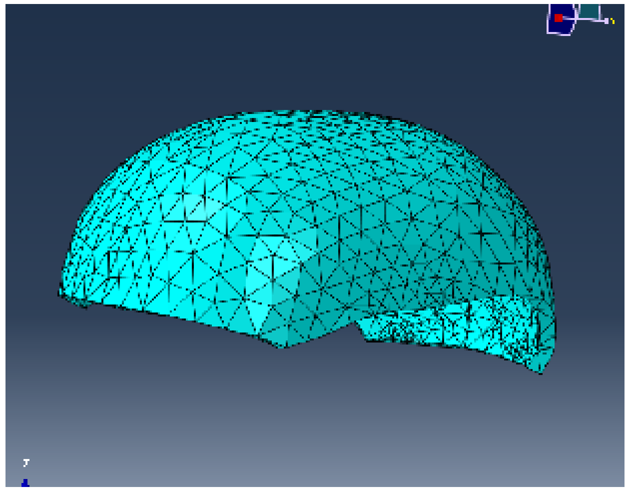


Figure 3.36: Top scalp mesh of FEA

Figure 3.37 shows the mesh of the total skull consisting of 11,314 nodes and 38,340 elements. Similarly, the type of element selected was linear tetrahedral (C3D4).

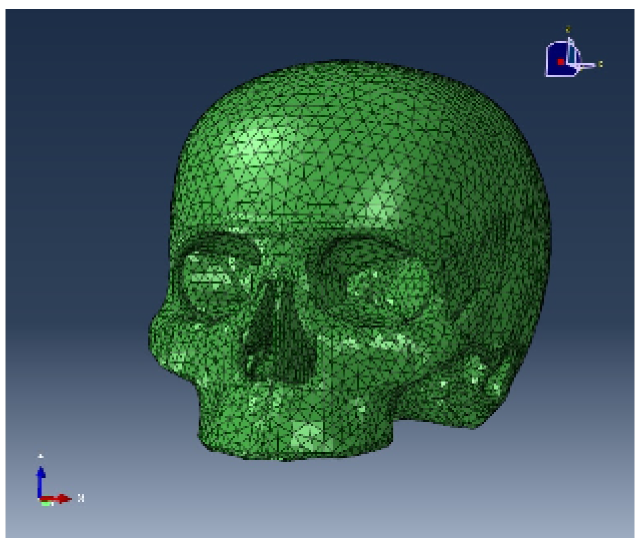


Figure 3.37: Skull mesh of FEA

Figure 3.38 is the mesh representation of the CFSF based on Kleiven (2003) with its average thickness of 2 mm. Its meshing is made up of 4,926 nodes, 2464 elements, 2460 linear hexahedral (C3D8) and 4 linear wedge elements (C3D6).

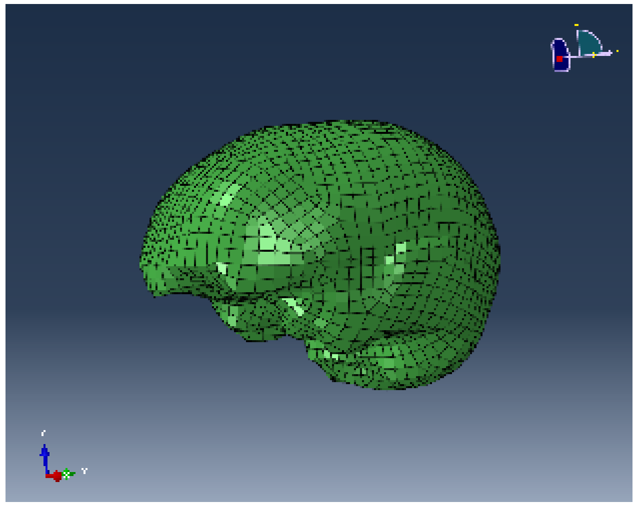


Figure 3.38: CSF mesh of FEA

Figure 3.39 shows the mesh of brain consisting of 6,326 nodes and 30,348 elements. The element type selected was linear tetrahedral (C3D4).

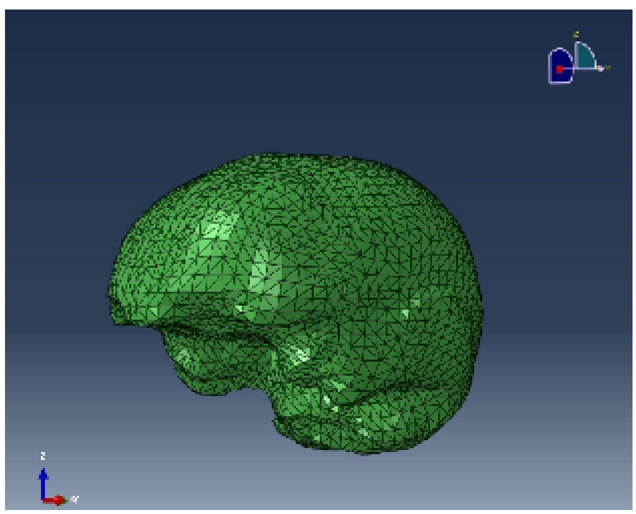


Figure 3.39: Brain mesh of FEA

Figure 3.40 shows the mesh of a sepak takraw ball consisting of 20,508 nodes and 7,896 elements. Similarly the type of element used was linear hexahedral (C3D8R).

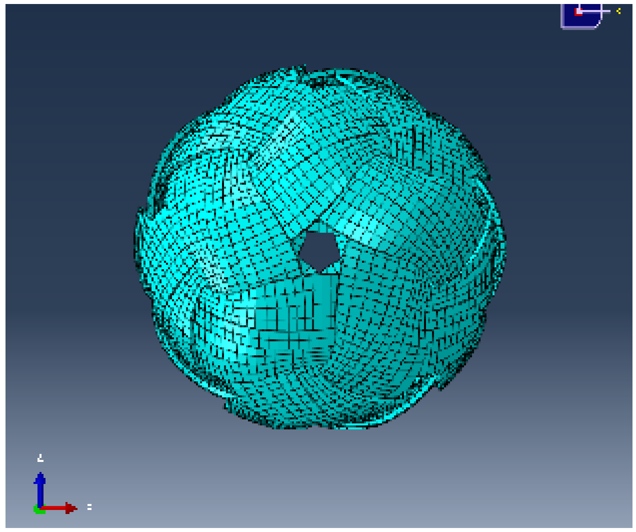


Figure 3.40: Sepak takraw ball mesh (Ahmad et al, 2012)

3.4.2.4 Interactions, Constraints, Loads and Boundary Conditions

The interaction between the head and sepak takraw ball model was specified as general *contact explicit* for the type and *dynamic explicit* for the step with 0.1 sec (100 ms) for the time period because based on the FE simulation, this was the period where the displacement of brain was already at rest. Additionally, the capacity or memory space of the computer could not support a simulation of more than 100 ms. Even for a 100 ms of simulation, it took one week for the device to achieve the result. The contact domains selected were self and surface pairs.

Following Miller et. al. (1998), the contact properties of 0.2 for friction coefficient was used. The tie constrain type was selected for the constraint between the inner surface of scalp and outer surface of the skull model.

Following Ahmad et al. (2012), the selected load type pressure for all inner surfaces of sepak takraw ball was 38,000 Pa with uniform distribution. Then, for the speed of sepak takraw ball, the predefined field type applied was velocity (see Table 3.12). Uniform was further selected for distribution and translational was selected for definition. The boundary condition of the skull model is as shown in Figure 3.41, with ENCASTRE type (U1=U2=U3=UR1=UR2=UR3=0).

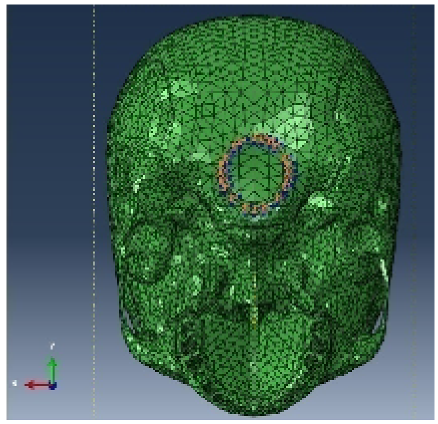


Figure 3.41: Region position of the boundary condition in skullbase

Table 3.12 explains the velocity value that was used as input in FE simulation. This speed value was obtained from the measurements in data analysis of the videos recorded during the championship. The overall data is presented in the next Table 4.37.

Table 3.12: Direction speed of sepak takraw ball heading in Abaqus

Position of heading	V_1 (x-axis)	V_2 (y-axis)	V_3(z-axis)	Resultant of speed
Front-forehead	0	13.5	-1.5	13.58
Side-forehead	0	10.46	-1.5	10.56
Top-forehead	0	10.17	-9	13.58

Figure 3.42 illustrates the position speed direction of sepak takraw ball for front-forehead heading after the speed data was inserted in FE simulation.

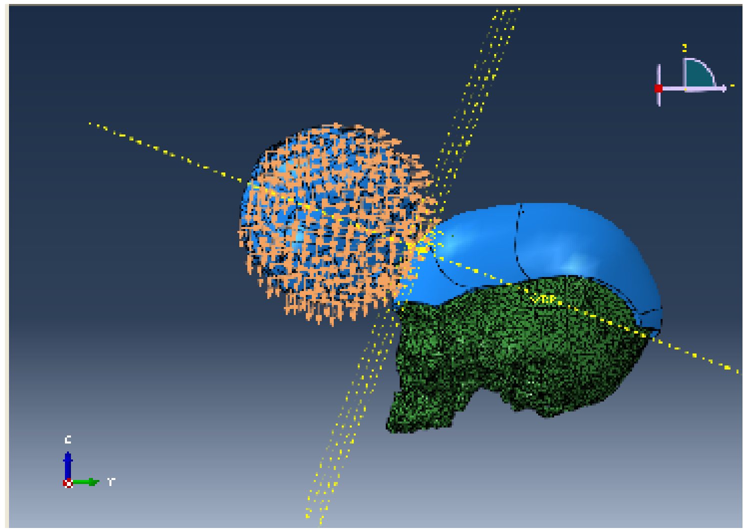


Figure 3.42: Direction of speed of sepak takraw ball for front-forehead heading

3.5 Validation of Results

For comparisons of the results, the results from interviews with the subjects were correlated with the levels of probability on the players' brain injury. This is further discussed in CHAPTER 4. For FE simulation results, the following parameters were measured, namely: displacement, velocity, acceleration, angular displacements, angular velocity, angular acceleration and impact force. To obtain the probability of concussion, the HIC and HIP were also calculated and is presented in CHAPTER 5. Additionally, a comparison of percentage difference between the results of the experiments and FE simulation were calculated. The comparisons made were on impact force, acceleration, contact time, and speed of sepak takraw ball before and after heading. The results are discussed in CHAPTER 5 and CHAPTER 6).

3.6 Summary

This chapter has provided an overview of the research frame work of this study comprising of 6 phases. Survey 1 was conducted with the subjects to obtain the possible MTBI symptoms, Survey 2 was on the anthropometric measurements of the player's head to obtain the head model of the Malaysian population, and Survey 3 was the data collection which recorded spikes failures from the killer players after heading the first ball. Finally, Survey 4 was conducted to record the games at the KFC-Utusan championship with a high speed camera to measure the speed of ball and positions of headings.

The material properties of brain used were based on the study by Willingier et. al. (1999) and Willinger and Baumgartner (2003). The assembly of the parts of models of the sepak takraw ball, and further the assembly of the scalp, skull, CSF and brain are presented.

This study would validate the results based on the comparisons from the experiments and FE simulations. The probability of concussion was calculated based on HIC and HIP.

RESULTS OF SURVEYS

4.1 Introduction

This chapter presents the results of the first survey, which were the questionnaires from interviews of 100 sepak takraw players from Peninsular Malaysia. The findings from the anthropometrics head data, observations during the championships and the results from the sepak takraw ball speeds are also presented.

4.2 Result of Interviews

This section presents the findings from the interviews conducted with the subjects. It presents the background of the players involved in sepak takraw such as their playing levels (professionals or amateurs), years of playing the sport and the number of hours of training per week.

4.2.1 Background of the Subject in Section A

Question (Q) A1 to A5 in Section A enquired the subjects' personal data such as their positions in the sepak takraw game and frequency of those positions played thus far. Table 4.1 shows the number of subjects grouped by their positions in the games.

Table 4.1: Positions of subjects in sepak takraw games

Player	Frequency	Percent
Feeder	26	26.0
Tekong	36	36.0
Killer	38	38.0
Total	100	100.0

Q-A6 referred to the subjects' skill level in the game; the results are presented in Table 4.2. The mean level of skill for each subject is 2.53 and the standard deviation is 0.915.

Table 4.2: Level of skill of the subjects

Level of player	Frequency	Percent
School/Institution	15	15.0
Club/Company	31	31.0
State/Territory	40	40.0

National	14	14.0
Total	100	100.0

Q-A7 inquired the game history of the player to find the age they started playing the game. The results are shown in Table 4.3. The mean starting age is 11.89 years and the standard deviation is 3.146.

Table 4.3: Time history of when subjects started to play

Age (year)	Frequency	Percent
8 to 10	35	35
11 to 13	41	41
14 to 16	18	18
17 to 19	6	6
Total	100	100

Q-A8 enquired on the training or exercise schedule, focusing on the number of days they played in a week. The result is shown in Table 4.4. The mean trainings or an exercise per week is 5.83 days and the standard deviation is 1.652 day.

Table 4.4: Total days of training per week for each subject

Day/week	Frequency (Subject)	Percent
1	2	2.0
2	3	3.0
3	6	6.0
4	12	12.0
5	13	13.0
6	4	4.0
7	60	60.0
Total	100	100.0

The average hour of exercise per day was asked in Q-A9 and the results are shown in Table 4.5. The mean hour of exercise per day is 2.58 and the standard deviation is 1.504.

Table 4.5: Average hour of exercises per day

Hour	Frequency	Percent
1 to 2	62	62
3 to 4	28	28
5 to 6	5	5
7 to 8	5	5
Total	100	100

Table 4.6 show the number of years of experience playing the game. The mean years of playing experience is 13.21 years and the standard deviation is 8.814.

Table 4.6: Total years of playing experiences

Year	Frequency	Percent
2 to 7	30	30
8 to 13	33	33
14 to19	12	12
20 to 25	17	17
26 to 31	5	5
32 to 37	2	2
38 to 43	0	0
44 to 49	1	1
Total	100	100

4.2.2 Mild Trauma Brain Injury (MTBI) Symptoms of the Player

Section B of the questionnaire required the subjects to answer 22 questions (Q-B1until B-22) which were related to the MTBI symptoms. The results were analyzed with the binomial method for the reliability test which was important to be conducted. Table 4.7 shows that the reliability test by using the Cronbach's Alpha value is 0.708, indicating that the data was acceptable.

Table 4.7: Reliability of subjects for the section B

Cronbach's Alpha	No of Items
.708	22

The questions in Section B were based on the Likert scale. The ordinal data were classified from effective (strongly agree and agree) and not effective (not agree). The binomial method was used to test the hypothesis developed as the following:

H_1 = MTBI is prevalent for the group of player.

H_0 = MTBI symptom is not prevalent for the group of player.

P < 0.05 means H_1 is accepted

P> 0.05 means H_1 is rejected and H_0 is accepted

The next following tables from Table 4.8 to Table 4.29 show the results for the 22 questions in Section B.

Q-B1 enquired on the occurrence of headaches after headings of high speed sepak takraw balls. The result is a significant value for P < 0.05 which means H_1 is accepted as shown in Table 4.8. Therefore headaches were felt by a majority of the players.

Table 4.8: Result of the binomial test of headache

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B1	Effect (H1)	88	.88	.000	Effect
	No Effect (H0)	12	.12		
Total		100	1.00		

The results from Q-B2 showed that a large number of the subjects did not feel pain in the neck because of headings. The significant value for P> 0.05 which indicates the hypothesis H_0, as shown in Table 4.9.

Table 4.9: Result of binomial test of neck pain

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B2	Effect (H_1)	14	.14	.000	No effect
	No Effect (H_0)	86	.86		
Total		100	1.00		

The results from Q-B3 showed that most of the subjects did not feel pain in the back because of headings, as the significance for P> 0.05 is H_0, as shown in Table 4.10.

Table 4.10: Result of binomial test of back pain

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B3	Effect (H1)	32	.32	.000	No effect
	No Effect (H0)	68	.68		
Total		100	1.00		

The results from Q-B4 also indicated no sleeping difficulties for a majority of the subjects, as the significance for P> 0.05 is H_0, as shown in Table 4.11.

Table 4.11: Result of binomial test of sleeping difficulties

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B4	Effect (H1)	16	.16	.000	No effect
	No Effect (H0)	84	.84		
Total		100	1.00		

Table 4.12 presents the result of binomial test for Q-B5 (significant of P>0.05 is H_0). It was found that most of the subjects did not experience any health effect as a direct result of sepak takraw ball hard headings.

Table 4.12: Result of binomial test of the effect of sepak takraw ball hard heading towards health

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B5	Effect (H_1)	47	.47	.242	No Effect
	No Effect (H_0)	53	.53		
Total		100	1.00		

From Q-B6, the subjects, in general, did not have any problems with their memory as the significance for P> 0.05 is H_0 (see Table 4.13).

Table 4.13: Result of binomial test of memory problems

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B6	Effect (H_1)	21	.21	.000	No effect
	No Effect (H_0)	79	.79		
Total		100	1.00		

From Q-B7, it was found that it was common for a majority of the subjects to forget where they put things as the significance for P < 0.05 is H_1 (see Table 4.14).

Table 4.14: Result of binomial test of forgetting where things are put (everyday)

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B7	Effect (H_1)	80	.80	.000	Effect
	No Effect (H_0)	20	.20		
Total		100	1.00		

Table 4.15 shows the result from Q-B8, where significance for P> 0.05 is H_0. This means that the subjects in general did not have difficulty to focus in following the game in progress.

Table 4.15: Result of binomial test of difficulty to focus in following the game in progress

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B8	Effect (H_1)	38	.38	.006	No effect
	No Effect (H_0)	62	.62		
Total		100	1.00		

Table 4.16 shows the result from Q-B9, where the subjects mainly did not have any difficulty effects in focusing (everyday) as the significance for P> 0.05 is H_0.

Table 4.16: Result of binomial test of difficulty in focusing (everyday)

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B9	Effect (H_1)	40	.40	.018	No effect
	No Effect (H_0)	60	.60		
Total		100	1.00		

Table 4.17 shows that the significance for $P < 0.05$ is H_1 for Q-B10, therefore a majority of the subjects agreed that they felt nervous when starting a game.

Table 4.17: Result of binomial test of feeling nervous in starting a game

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B10	Effect (H_1)	68	.68	.000	Effect
	No Effect (H_0)	32	.32		
Total		100	1.00		

Table 4.18 shows that the significance for P> 0.05 is H_0 for Q-B11, indicating that most of the subjects did not have any problems with blurry vision due to headings.

Table 4.18: Result of binomial test of blurry vision

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B11	Effect (H_1)	24	.24	.000	No effect
	No Effect (H_0)	76	.76		
Total		100	1.00		

Table 4.19 shows the result from Q-B12, indicating the significance for P> 0.05 is H_0, meaning that a majority of the subjects did not feel nauseated after headings.

Table 4.19: Result of binomial test of feeling nauseated (want to vomit)

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B12	Effect (H_1)	5	.05	.000	No effect
	No Effect (H_0)	95	.95		
Total		100	1.00		

Table 4.20 shows that the significance for P> 0.05 is H_0 for Q-B13, suggesting that most of the subjects did not feel sleepy after headings.

Table 4.20: Result of binomial test of feeling sleepy

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B13	Effect (H_1)	22	.22	.000	No effect
	No Effect (H_0)	78	.78		
Total		100	1.00		

The result for Q-B14 is shown in Table 4.21, indicating the significance for P> 0.05 is H_0, meaning that a large number of the subjects did not feel confused after impact of sepak takraw ball in the second view.

Table 4.21: Result of binomial test of feeling confused after impact in the second view

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B14	Effect (H_1)	24	.24	.000	No effect
	No Effect (H_0)	76	.76		
Total		100	1.00		

Table 4.22 shows the result for Q-B15 where the significance for $P < 0.05$ is H_1, signifying that most of the subjects did have tears coming out of their eyes after high speed takraw ball headings.

Table 4.22: Result of binomial test of having tears coming out of your eyes

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B15	Effect (H_1)	65	.65	.003	Effect
	No Effect (H_0)	35	.35		
Total		100	1.00		

Table 4.23 shows the result for Q-B16 where the significance for $P < 0.05$ is H_1, signifying that a majority of the subjects did feel emotional after hard headings.

Table 4.23: Result of binomial test of feeling emotional

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B16	Effect (H_1)	64	.64	.006	Effect
	No Effect (H_0)	36	.36		
Total		100	1.00		

Table 4.24 shows the result for Q-B17 where the significance for P> 0.05 is H_0, indicating that most of the subjects did not find their vision to be doubled after hard headings.

Table 4.24: Result of binomial test from doubled vision

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B17	Effect (H_1)	19	.19	.000	No effect
	No Effect (H_0)	81	.81		
Total		100	1.00		

From Q-B18, it was found that most of the subjects did not have any hearing problems after hard headings, where significance for P> 0.05 is H_0, as shown in Table 4.25.

Table 4.25: Result of binomial test of hearing problems

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B18	Effect (H_1)	8	.08	.000	No effect
	No Effect (H_0)	92	.92		
Total		100	1.00		

The result from Q-B19 indicated that most of the subjects did hear sounds of droning in their ears after hard headings, as the significance for $P < 0.05$ is H_1 (see Table 4.26).

Table 4.26: Result of binomial test of hearing sounds of droning in the ears

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B19	Effect (H_1)	68	.68	.000	Effect
	No Effect (H_0)	32	.32		
Total		100	1.00		

Table 4.27 shows the result from Q-B20. The significance $P < 0.05$ is H_1 which indicated that a majority of the subjects' felt that their eyes were more sensitivity toward bright lights after headings.

Table 4.27: Result of binomial test of eyes feeling sensitive toward bright lights

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B20	Effect (H_1)	84	.84	.000	Effect
	No Effect (H_0)	16	.16		
Total		100	1.00		

Table 4.28 shows the result from B-Q21. Based on the significance of $P> 0.05$ is H_0, it was found that most of the subjects did not feel their ears sensitive towards loud noises.

Table 4.28: Result of binomial test of the subject ears feel sensitive toward loud noises

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B21	Effect (H_1)	29	.29	.000	No effect
	No Effect (H_0)	71	.71		
Total		100	1.00		

Finally, from Q-B22, it was found that a majority of the subjects did feel unbalanced after hard headings as the significance for $P < 0.05$ is H_1 (see Table 2.29).

Table 4.29: Result of binomial test of feeling unbalanced after hard headings

No.	Category	N	Observed Prop.	Exact Significant (1-tailed)	Decision
Q-B22	Effect (H_1)	67	.67	.001	Effect
	No Effect (H_0)	33	.33		
Total		100	1.00		

4.2.3 Positions of Heading on the Head

This section explains the results from the five questions in Section C with regard to the positions of heading of the sepak takraw ball. Information on whether the subjects were wearing any particular head band during their games, the number of headings they performed during training, the area of headings in which they felt any effects or reactions after the headings were collected. The players were also enquired on the movements of their head after heading the sepak takraw balls.

Q-C1 raised the issue on the use of headbands. The results, summarised in Table 4.30, showed that most of the players, approximately 78%, did not wear any headbands. Out of the 22% who did wear headbands, 21% wore cotton bandana-styled headbands and only 1% wore a rubber-cotton mix terry headbands.

Table 4.30: Have you ever worn a headband on your head?

Answer	Frequency	Percent
Not wearing	78	78.0
Wearing Cotton	21	21.0
Wearing rubber fabric	1	1.0
Polyester	0	0
Total	100	100.0

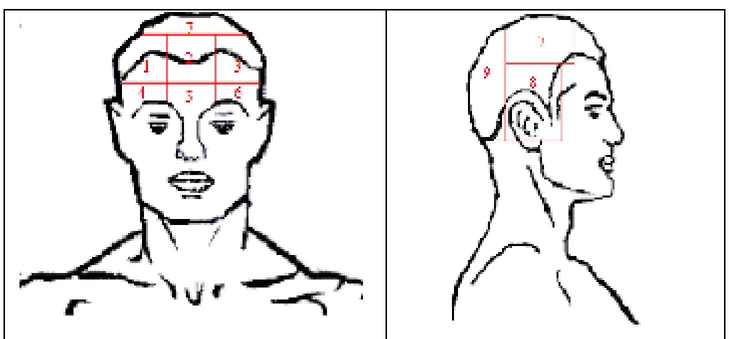
Those who did not wear any headbands reasoned that the headbands were generally unusual, discomforting and affect their ability to control the sepak takraw ball.

Q-C2 enquired on the frequency of heading a ball in a one day training session/game. The answers from the subjects are summarized in Table 4.31.The results showed that the majority of the subjects (32%) had performed 0-20 count of headings per training or game session. On the other hand, only a minority of subjects (7%) had performed more than 101 of headings per training or game session. The subjects also informed that for those who were in the position of the killer player and played for the national team, they would endure up to 1000 ball headings per training session.

Table 4.31: Head the ball in one-day training session

Heading (time)	Frequency	Percent
0-20	32	32.0
21-40	25	25.0
41-60	20	20.0
61-80	8	8.0
81-100	8	8.0
more than 101	7	7.0
Total	100	100.0

Q-C3 inquired the location of the subjects' typical headings based on the figures provided in Figure 4.1. They were allowed to tick at more than one location.



Front View | Side view

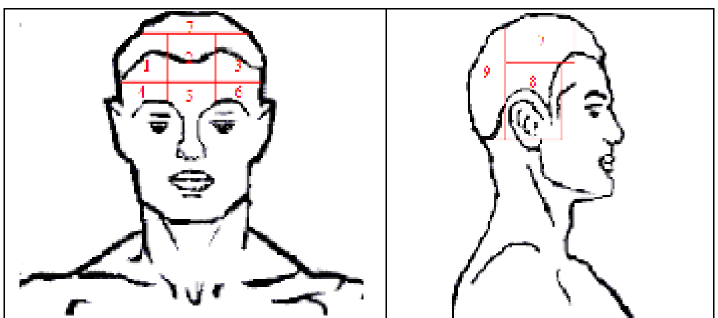
Figure 4.1: Location of headings on the head

Table 4.32 summarizes the heading based on head locations. The findings showed that the frequencies of headings based on the head location were conducted mostly (100%) at location no. 2. This indicates that it was the typical location for every subject to perform headings in sepak takraw games. The locations less used for headings were at no. 4 (3%) and no. 6 (3%).

Table 4.32: Frequencies of heading base on location of heading

Location of heading	Responses		Percent of cases
	N	Percent	
1	76	22.1	76.0
2	100	29.1	100.0
3	76	22.1	76.0
4	3	0.9	3.0
5	6	1.7	6.0
6	3	0.9	3.0
7	61	17.7	61.0
8	9	2.6	9.0
9	10	2.9	10.0
Total	344	100.0	344.0

Q-C4 enquired to the location of pain or headache felt after a ball heading, by indicating the pain location as shown in Figure 4.2.



Front View	Side view

Figure 4.2: Location of pain/headache felt after heading

It was found that after headings, a majority of the subjects felt pain or headache in locations no. 4, no. 5 and no. 6; each location was felt by more than 60% of the subjects, as shown in Table 4.33. Location no. 2, at 11%, was the least part for pain or headaches after a heading.

Table 4.33: Frequencies of pain/headache felt during /after a heading base on heading locations

Location of feel pain/ headache	Responses		Percent of cases
	N	Percent	
1	29	8.0	29.0
2	11	3.0	11.0
3	30	8.2	30.0
4	68	18.7	68.0
5	65	17.9	65.0
6	67	18.4	67.0
7	27	7.4	27.0
8	58	15.9	58.0
9	9	2.5	9.0
Total	364	100.0	364.0

Lastly, Q-C5 enquired on the head movement of the subjects after headings of receiving sepak takraw balls (also known as 'reply header'), particularly after fast ball services. Basically, it was to inquire whether the subjects felt movements of the head after receiving the ball from services in the game. This information was important for subsequent use in FE simulation to closely simulate actual conditions. Based on the findings summarised in Table 4.34, most of the subjects find that their heads did not move after receiving the ball from services.

Table 4.34: Result of moving of the head after receiving the ball from services

Reaction of player	Frequency	Percent
Moving	0	0
No moving	89	89.0
Sometimes moving	11	11.0
Total	100	100.0

4.3 Result of Anthropometrics Head Data

This section presents the results from the anthropometrics data measurements from the subjects. The measurements are summarised in Table 4.35.

Table 4.35: Anthropometrics data of subject

Dimension		Mean	5^{th}% tile	50^{th}% tile	95^{th}% tile
1	Weight (kg)	63.3	49.6	60.0	86.2
2	Stature (mm)	1676	1605	1676	1752
3	Head length (mm)	182	170	180	190
4	Head breadth (mm)	157	145	155	165
5	Tragion to top of head (mm)	134	116	130	148
6	Menton-sellion length (face length) (mm)	120	102	120	136
7	Bizigomatic breadth headboard (mm)	123	110	122	135
8	Interpupillary breadth (mm)	57	48	60	64
9	Head circumference (mm)	538	517	544	572
10	Neck circumference (mm)	351	315	347	398

The data in Table 4.35 was subsequently used to improve the CAD model of the head used in this study. The CAD model was configured to fit within 50% tile for the Malaysian population of Sepak Takraw players.

4.4 Result of Observation

Observation of headings at the Sepak Takraw World Cup 2011 was made to examine the subsequent movements of the killer player after receiving a hard heading. The player was also monitored to see whether the same killer player could subsequently perform a spike for the third sepak takraw ball after the heading of the first sepak takraw ball in a game turn. It is known that in Sepak Takraw games, the ball from the first service is received by the killer player by heading. Typically, in a service, the killer player receives it with heading, and then the feeder player delivers the ball near to the net for the same killer player to perform a spike or smash on the ball.

During the observations, the number of failed spikes by the killer player was noted. The failure referred here was divided into two categories: a.) getting the sepak takraw ball stuck in the net, or b.) getting the ball out off the court area. Table 4.36 shows the data of failed spikes by the killer players after receiving hard headings.

Table 4.36: Data of failed spikes in 2011 Kuala Lumpur

Sample of games (set)	Heading from first sepak takraw ball service		Number of failed spikes by the killer players after receiving hard headings
	Team	vs Team	
1 (5 set)	12 (TPE)	17 (FRA)	15
2 (3 set)	5 (CHN)	4 (VNM)	5
3 (3 set)	4 (INA)	3 (CHE)	4
4 (3 set)	8 (KOR)	3 (IND)	6
5 (3 set)	1 (MAS)	3 (PHI)	2
6 (3 set)	7 (IND)	6 (CAM)	6
7 (3 set)	2 (PAK)	7 (LAO)	4
8 (3 set)	2 (BAN)	5 (THA)	2
9 (3 set)	3 (JPN)	5 (AUS)	5
10 (3 set)	14 (SRI)	5 (SIN)	8
11 (3 set)	3 (KOR)	4 (MYA)	4
12 (5 set)	13 (SIN)	21(IND)	15
13 (3 set)	5 (THA)	1 (INA)	1
14 (3 set)	8 (JPN)	9 (TPE)	6
15 (3 set)	8 (BRU)	5 (GER)	8
16 (3 set)	12 (MAS)	10 (SIN)	6
17 (3 set)	2 (MYA)	7 (THA)	2
18 (3 set)	3 (MAS)	4 (THA)	2
Total	231 headings		101

Table 4.36 shows that the number of failed spikes by the killer players after hard headings from first ball of service was quite high at 101 failures (43.72%) from 231 total numbers of trials. The cause of the failures, relating to the results from the interviews, could be due to the effect of various problems that the subjects felt after hard headings which were discovered in this study, namely headache (refer to Table 4.8), unbalance (refer to Table 4.29), tears coming out of their eyes (refer to Table 4.22), and

unable to control their emotion (refer to Table 4.23). The correlation from the interviews was then correlated with the results from the simulation of finite element model which is elaborated in CHAPTER 5. The failure of the killer spikes was may be attributed to MTBI.

4.5 Result of Sepak Takraw Ball Speed

A Phantom™ high speed camera was used to capture actual headings during tournament games. Since the high speed camera requires sufficient lighting, games in open areas such the KFC-Utusan Championship were a good site for high speed captures. Figure 4.3 shows some photographs of actual headings in the games recorded using the high speed camera.

Figure 4.3: Picture of high speed heading during the games

Table 4.37 shows 17 headings of the speed of sepak takraw balls a few seconds before heading taken at the KFC-Utusan championship 2011. The average speed of sepak takraw balls before heading was 12.27 m/s. Good sample headings, namely Heading 17 for front-forehead, Heading 15 for top-forehead and Heading 10 for side-frontal heading as listed in Table 4.37, were selected to be used for the FE simulations.

Table 4.37: The of speed takraw before headings

Sample	Speed (m/s)
Heading 1	13.27
Heading 2	11.96
Heading 3	11.31
Heading 4	13.44
Heading 5	11.05
Heading 6	10.72
Heading 7	12.70
Heading 8	12.83
Heading 9	13.24
Heading 10	10.56
Heading 11	13.46
Heading 12	10.62
Heading 13	12.92
Heading 14	10.27
Heading 15	13.58
Heading 16	13.12
Heading 17	13.58

4.6 Discussion and Summary

The 100 subjects who participated in the interview consisted of feeder (26 %), tekong (36%) and killer (38%) players. A majority of the subjects (78%) did not wear or prefer headbands because they found them to be uncomfortable and disturb their control when performing headings of the sepak takraw balls. From the interviews on MTBI, after headings, 88% of the subjects felt headaches, 80% regularly forgot where they put things (everyday), 68% felt nervous before starting a game, 65% had tears coming out of their eyes, 64% felt emotional, 68% heard sound of droning, 84% felt their eyes were sensitive toward bright lights and 67% felt unbalanced. These findings suggest that the subjects may be experiencing MTBI especially as most of them were not wearing any headbands for possible head protections.

From the survey on the speeds of sepak takraw ball, there were 17 utilizable samples obtained from the video recordings, and three were selected for the FE simulation due to image clarity. The average speed of the sepak takraw balls before heading was 12.27 m/s, which can be considered as fast balls. Therefore, possible MTBI experienced by the players could also be correlated to the number of failed spikes performed by the killer players after headings from the first ball service. From a total of 231 headings observed in this study, 101 (43.72 %) resulted in failed spikes or smash.

Comparison of the CAD model with the measured anthropometric head data showed a 95%tile agreement of Malaysian population of the subjects. The CAD model was reduced in size by 5.66 % to correspond to 50%tile of the subject population.

RESULT OF FINITE ELEMENT ANALYSIS

5.1 Introduction

This chapter presents the results of comparison of simulation data of FEA and data from experiment of heading. The comparison between FEA simulation and image analysis from the sepak takraw championship were made of three heading positions, namely the front-forehead, top-forehead and side-forehead of heading. The FEA simulation results include the contact time of heading, impact force of heading, displacement of skull, displacement of brain, acceleration of brain and displacement of frontal-brain, occipital-brain. For validation, the speeds of the sepak takraw ball were compared between data from the championship and FEA simulation. The values of HIC and HIP for the three positions of heading were also computed.

5.2 FEA Results of Drop-Test Heading on the Front-Forehead Area

This section presents results of measurement of the total impact force of the head, displacement of the skull, displacement of the whole brain, 6 points displacement in the frontal-brain and 6 points displacement in the occipital-brain of drop-test heading at the front-forehead location. Figure 5.1 is the image from finite element simulation of drop-test heading. The discussion of the results is presented in section 5.2.2

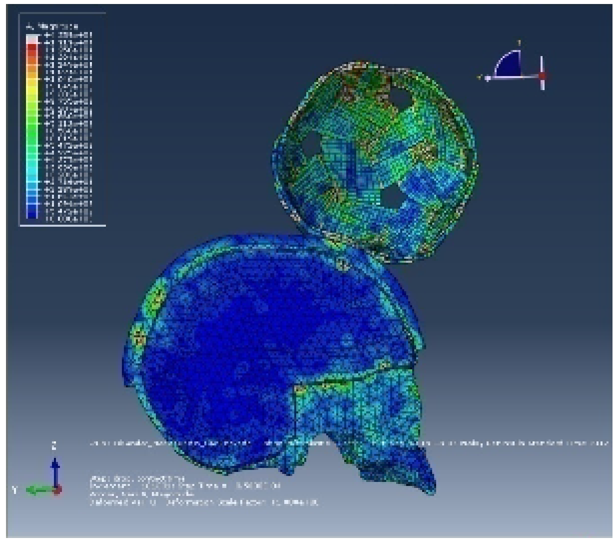


Figure 5.1: Finite element simulation of drop-test heading

Figure 5.2 shows the total impact force of the head during the drop-test heading, with a contact time of 0.01122 sec (11.22 ms), a maximum force of 221.06 N on the head and the speed of ball before impact was 4.32 m/s.

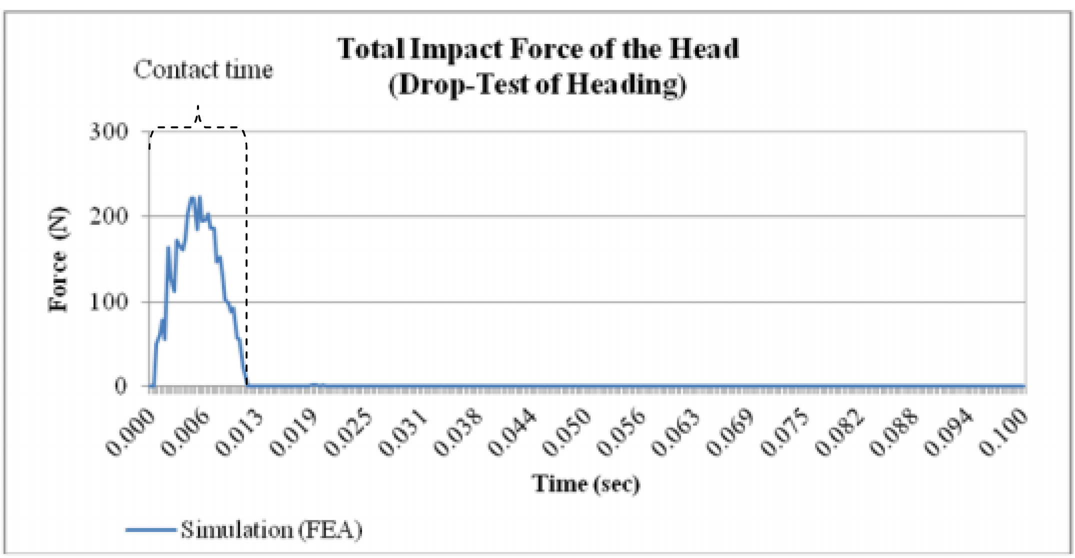


Figure 5.2: Total Impact force of the head at drop-test heading

Figure 5.3, shows the average accelerations of the whole brain. The maximum magnitudes for the positive and negative directions in x-axis are 34.14 m/s^2 and -21.07

m/s^2. The maximum magnitudes for the positive and negative directions in the y-axis are 30.62 m/s^2 and -28.47 m/s^2. The maximum magnitudes of the positive and negative direction in the z-axis are 37.20 m/s^2 and -20.15 m/s^2.

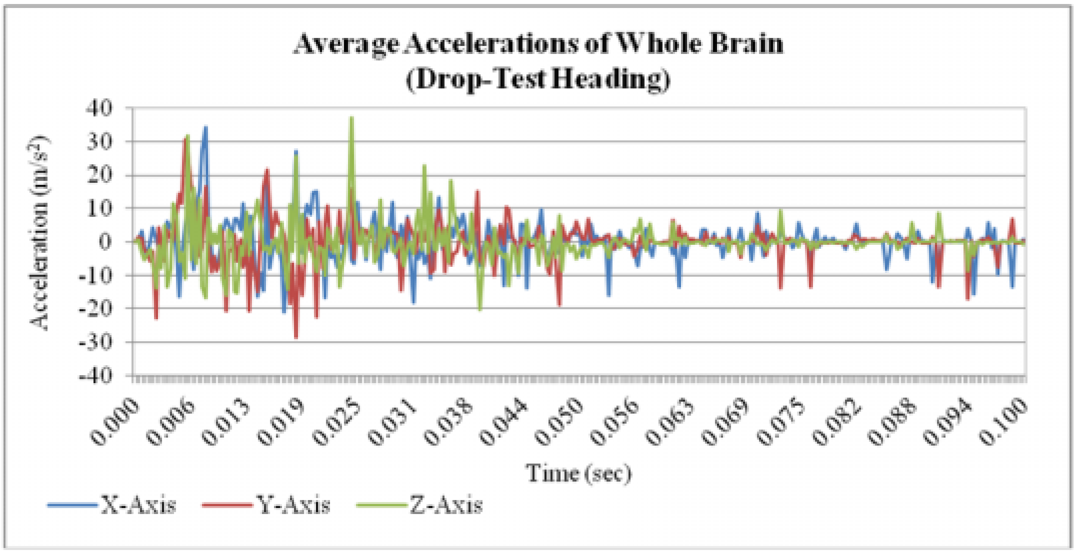


Figure 5.3: Average accelerations of whole brain for drop-test heading

Figure 5.4 presents the displacement of the skull during the drop-test heading. The maximum displacement during impact is 0.008 mm and the minimum is -0.026 mm, in the y-axis. This is compared to the displacements after impact at 100 ms from simulations which are 0.00009 mm for the x-axis -0.0055 mm in the y-axis and z-axis at 0.0006 mm.

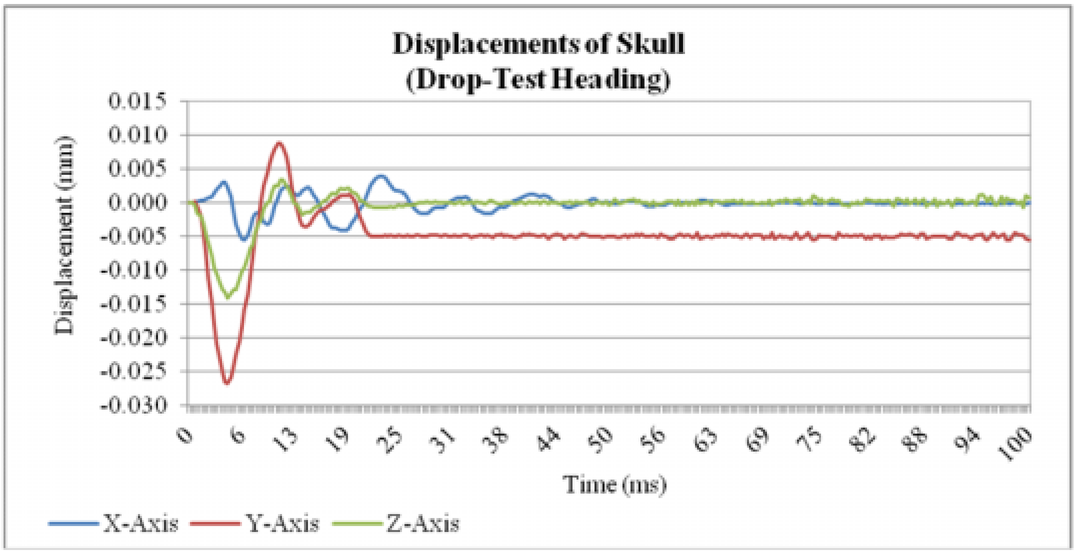


Figure 5.4: Displacement of skull for drop-test heading

Figure 5.5 shows the displacements of the whole brain during the drop-test heading. The maximum displacement during impact is 0.013 mm in the x-axis, and the minimum is -0.046 mm in the y-axis. This is compared to simulation where after impact at 100 ms, the displacements are -0.001 mm in the x-axis, -0.016 mm at the y-axis and 0.002 mm in the z-axis.

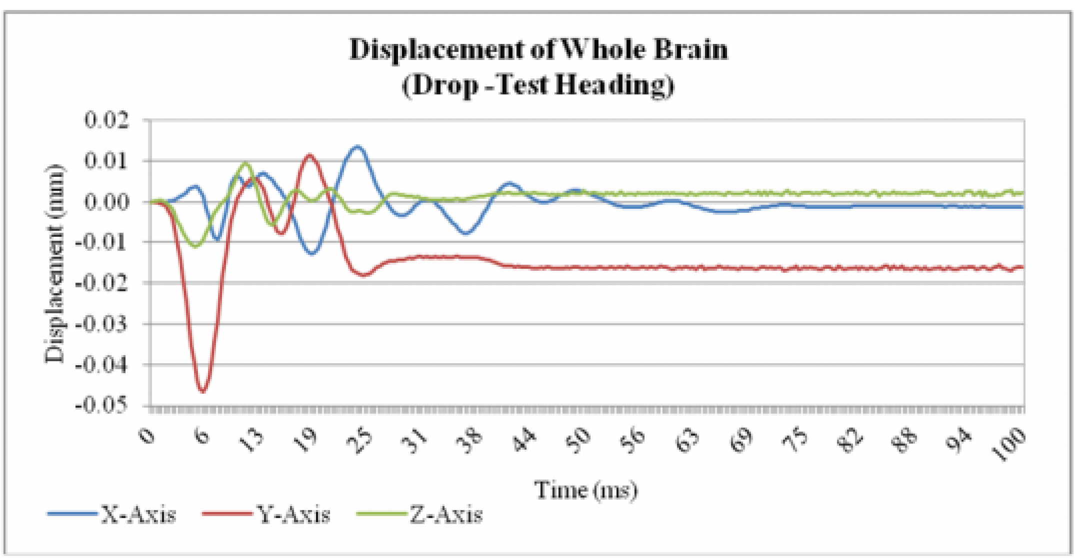


Figure 5.5: Displacements of whole brain for drop-test heading

Figure 5.6 shows the displacements of the frontal-brain in the x-axis direction during drop-test heading. The maximum of displacement is 0.046 mm and the minimum is -0.031 mm, both of them at point 1. The displacements after impacts at 100 ms during simulation at point 1 is 0.003 mm, point 2 is 0.002 mm, point 3 is 0.003 mm, point 4 is 0.002 mm, point 5 is 0.002 mm and point 6 is 0.004 mm.

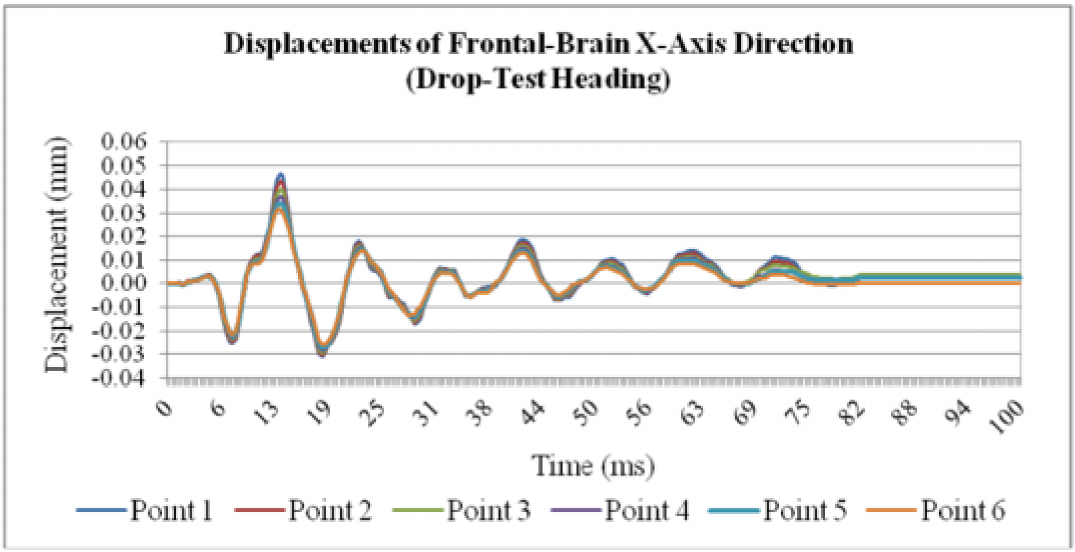


Figure 5.6: Displacements of frontal-brain x-axis direction for drop-test heading

Figure 5.7 shows the displacements of the frontal-brain in the y-axis direction during the drop-test heading. The maximum of displacement during impact is 0.025 mm and the minimum is -0.074 mm, both of them at point 1. The displacements after impact at 100 ms of simulation are point 1: - 0.035 mm, point 2: -0.031 mm, point 3: -0.033 mm, point 4: -0.033 mm, point 5: -0.028 mm and point 6: -0.030 mm.

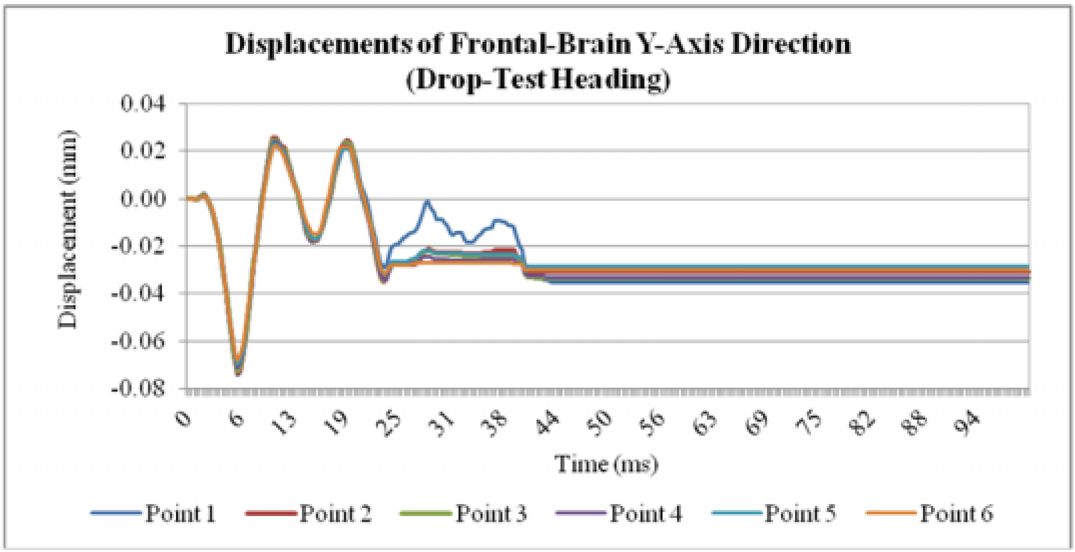


Figure 5.7: Displacements of frontal-brain y-axis direction for drop-test heading

Figure 5.8 shows the displacements of the frontal-brain in the z-axis direction during the drop-test heading. The maximum of displacement during impact is 0.029 mm and the minimum is -0.057 mm, both of them at point 1. The displacements after impact at 100 ms of simulation are point 1: 0.004 mm, point 2: -0.0001 mm, point 3: 0.006 mm, point 4: 0.003 mm, point 5: 0.0001 mm, and point 6: -0.0009 mm.

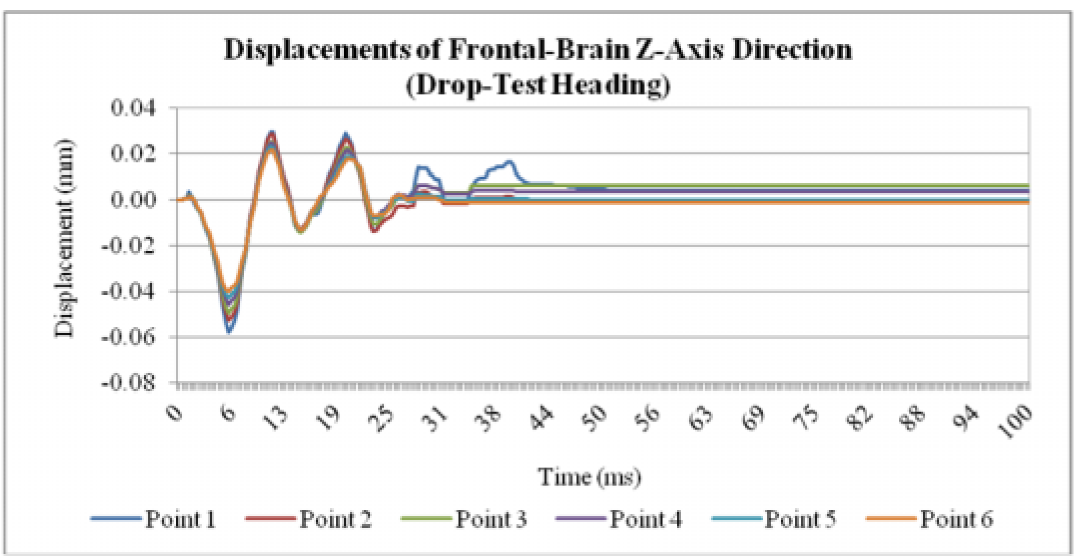


Figure 5.8: Displacements of frontal-brain z-axis direction for drop-test heading

Figure 5.9 shows the displacements of the occipital-brain in the x-axis direction during drop-test heading. The maximum of displacement during impact is 0.022 mm at point 1 and the minimum is -0.015 mm, both of them at point 1. Then, the displacements after impact at 100 ms of simulation are at point 1: -0.002 mm, point 2: -0.0005 mm, point 3: -0.004 mm, point 4: -0.004 mm, point 5: -0.002 mm.

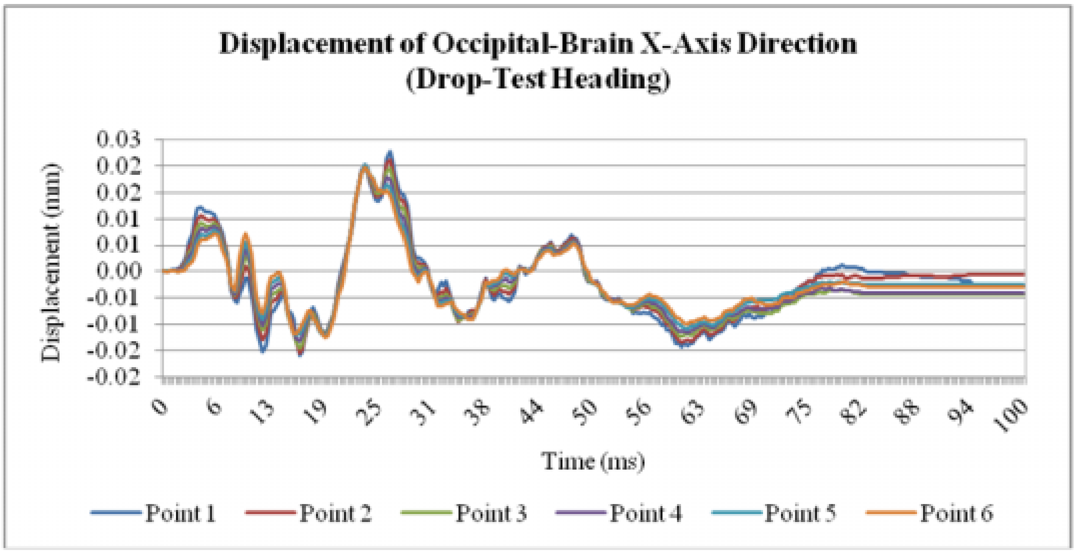


Figure 5.9: Displacements of occipital-brain x-axis direction for drop-test heading

Figure 5.10 shows the displacements of the occipital-brain in the y-axis direction during drop-test heading. Then, the maximum of displacement is 0.013 mm at point 6 and the minimum is -0.047 mm at point 2. The displacements after impact at 100 ms of simulation are at point 1: -0.030 mm, point 2: -0.027 mm, point 3: -0.018 mm, point 4: -0.020 mm, point 5: -0.017 mm and point 6: -0.015 mm.

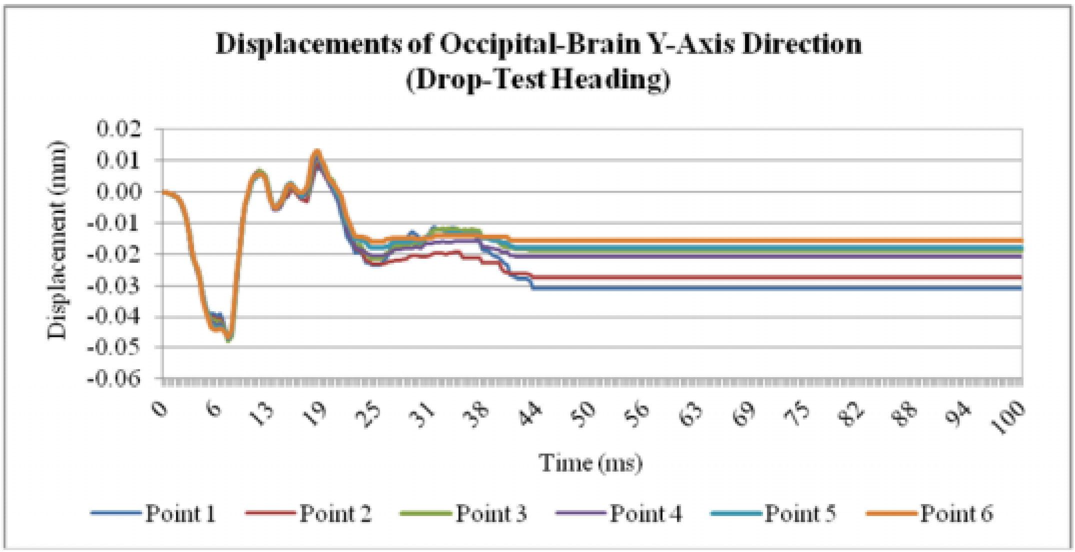


Figure 5.10: Displacements of occipital-brain y-axis direction for drop-test heading

Figure 5.11 shows the displacements of the occipital-brain in the z-axis direction during drop-test heading. The maximum of displacement during impact is 0.044 mm at point 1 and the minimum is -0.018 mm at point 1. The displacements after impact at 100 ms of simulation are at point 1: 0.008 mm, point 2: -0.002 mm, point 3: 0.001 mm, point 4: -0.0006 mm, point 5: -0.005 mm and point 6: -0.002 mm.

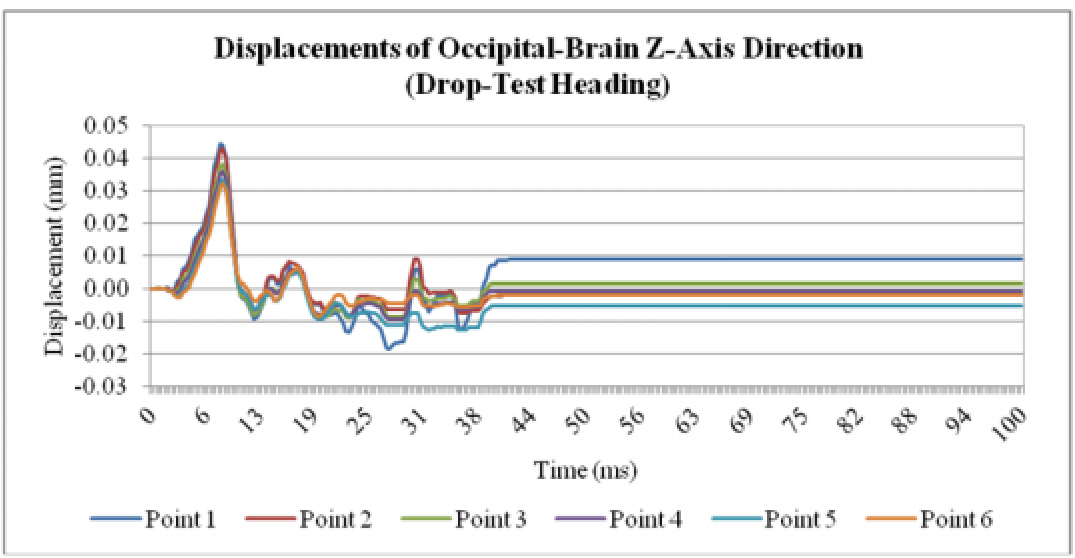


Figure 5.11: Displacements of occipital-brain z-axis direction for drop-test heading

5.2.1 Results of Validation from the Drop-Test of Sepak Takraw Ball Heading in Experiment

This section presents the results of validation of the experiment and simulation of the drop-test of sepak takraw ball heading. The validation refers to the speed of ball before and after heading, contact time of the sepak takraw ball in the experiment by using the high speed camera and the simulation from finite element analysis.

Figure 5.12 shows the speed of the centre of the sepak takraw ball from drop-test heading. The difference between simulation and experiment of the sepak takraw ball speeds before and after heading in the drop-test is found to be 4.5%. In Table 5.1, the experimental data was collected at the laboratory by using a high speed camera with the Salim sepak takraw ball. The camera was only recorded until 0.069 sec (69 ms) after impact. In the table, it can be seen that the position of the sepak takraw ball in the experiment is recreated in simulation.

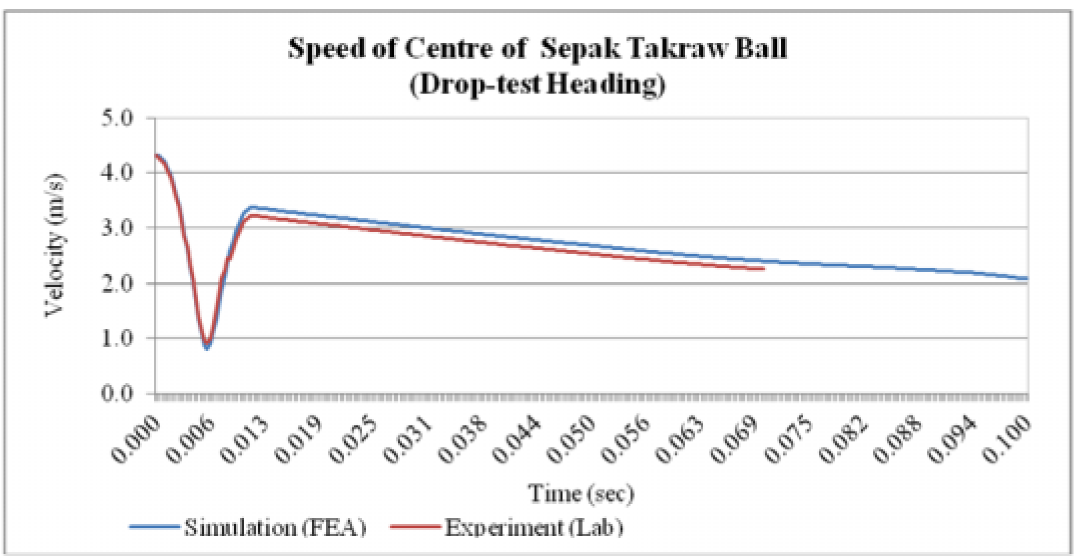
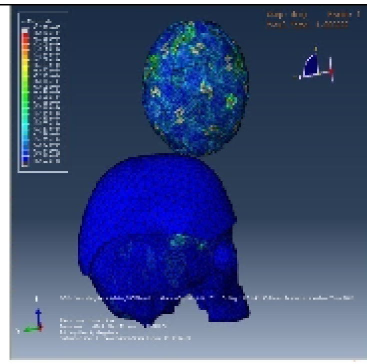
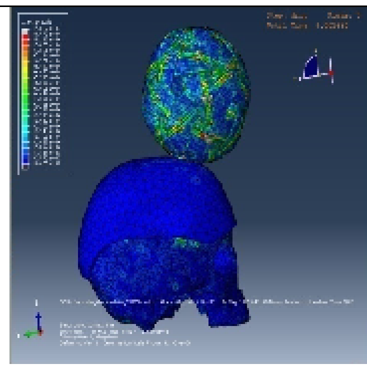
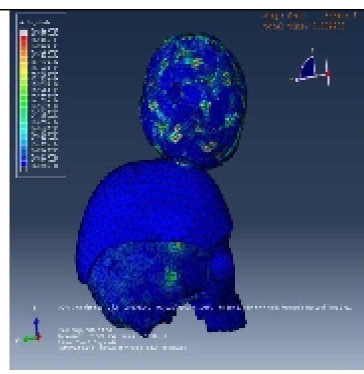
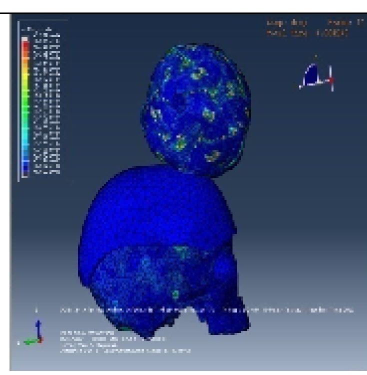
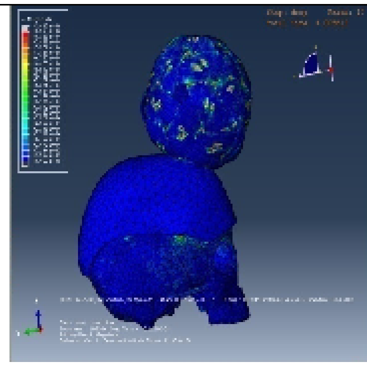
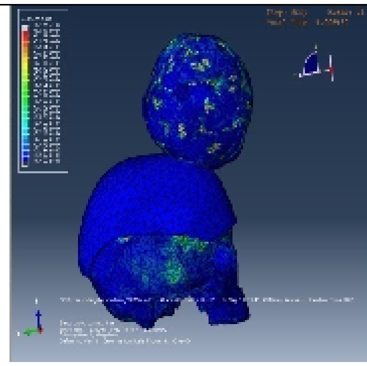
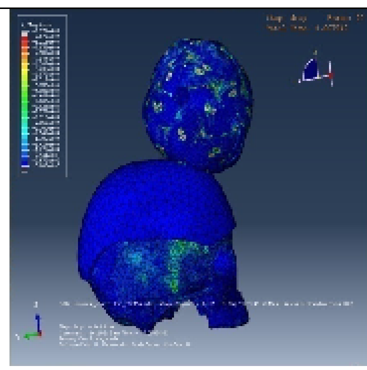
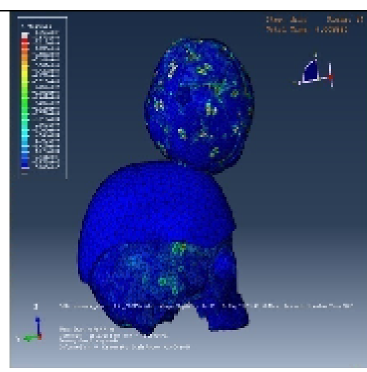
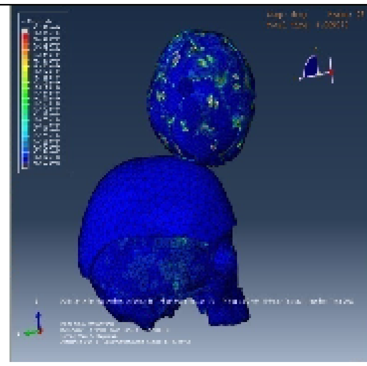
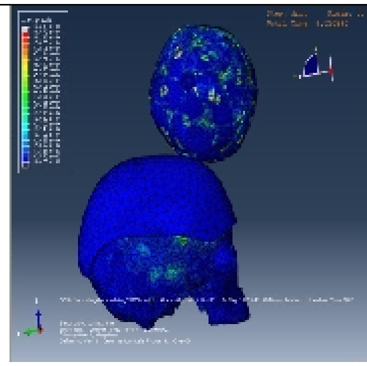


Figure 5.12: Speed of centre of sepak takraw ball for drop-test heading

Table 5.1: Contact time experiment of heading in the laboratory

No frame (ms)	FEA Simulation	High Speed Camera
Frame 1 starting the contact		
Frame 2		
Frame 3		
Frame 4		

Frame 5		
Frame 6		
Frame 7		
Frame 8		

Frame 9		
End of drop test heading		
	The time is 10.89 ms	The time is 10.0 ms

Furthermore, Table 5.1 shows the contact time of heading in the experiment is 10.0 ms compared with the simulated (FEA) contact time of 10.89 ms. The difference is 8.17 % for the free fall of the sepak takraw ball heading.

5.2.2 Head Injury Criterion and Head Impact Power of Drop-Test Heading

The following section presents important measurements, such as the displacement, velocity, acceleration in the centre of gravity of the brain, angular acceleration and contact time, for the calculation of the head injury criterion and head impact power of drop-test heading.

Firstly, Figure 5.13 presents the displacement of the centre of gravity of brain from drop-test of sepak takraw ball for front-forehead heading. The maximum of displacement during impact is 0.032 mm in y-axis and the minimum is -0.055 mm in y-axis. After impact at 100 ms of simulation, the displacements are -0.001 mm for x-axis, -0.004 mm for y-axis and 0.0003 mm for z-axis.

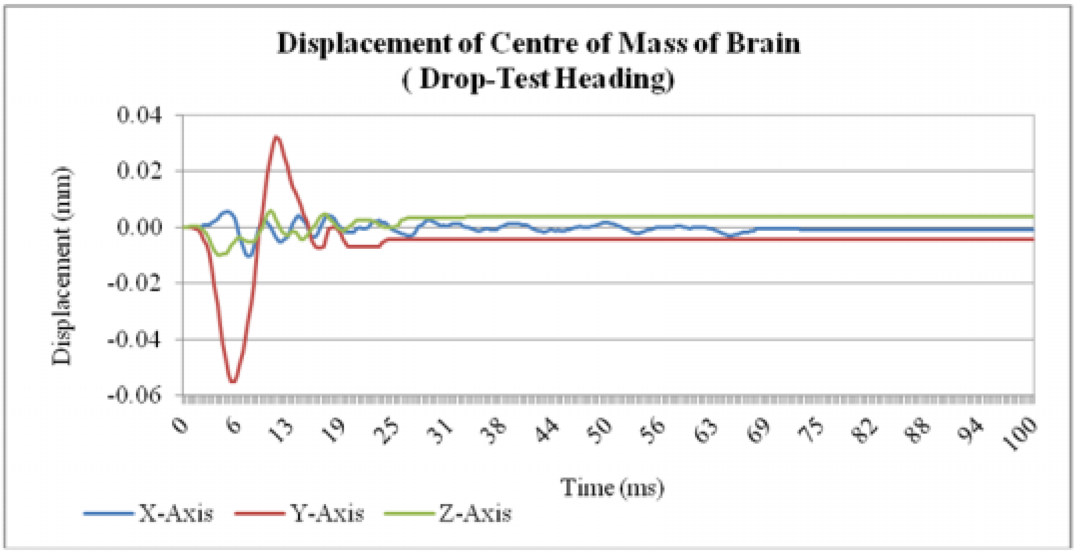


Figure 5.13: Displacement of the centre of gravity of brain from drop-test heading

Figure 5.14 shows the velocity of centre of gravity of brain from drop-test of sepak takraw ball for front-forehead heading. The maximum of velocity is 0.030 m/s and the minimum is -0.025 m/s in y-axis.

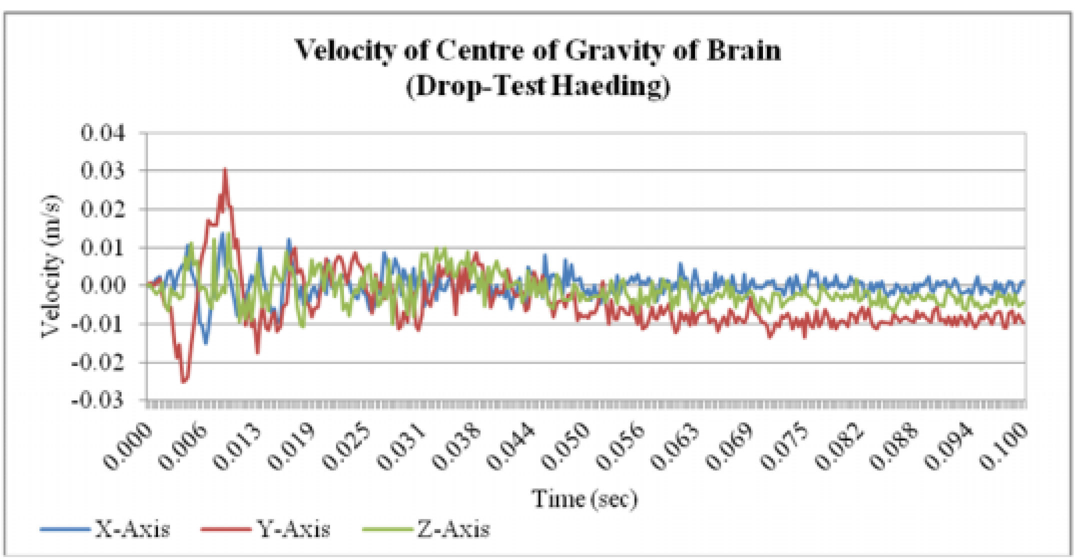


Figure 5.14: Velocity of centre of gravity of brain from drop-test heading

Figure 5.15 shows the acceleration of the centre of gravity of brain from drop-test of sepak takraw ball for front-forehead heading. The maximum magnitudes for positive and negative direction of accelerations in x-axis are 1176.7 m/s^2 and -1056.0 m/s^2. The maximum magnitudes for positive and negative direction of accelerations in y-axis are 1309.2 m/s^2 and -1032.2. And finally in the z-axis are 1151.6 m/s^2 and -1019.1 m/s^2.

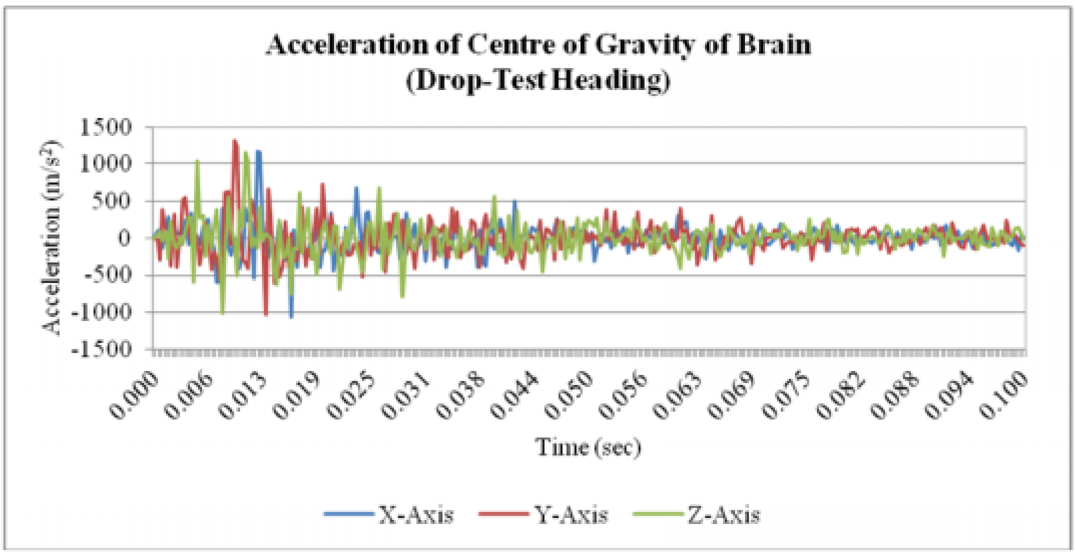


Figure 5.15: Acceleration of the centre of gravity of brain from drop-test heading

Figure 5.16 shows the angular displacements of the centre of gravity of brain from drop-test of sepak takraw ball for front-forehead heading. The maximum of the angular displacement is 0.0006 rad and the minimum is -0.0001 rad, both of them in y-axis.

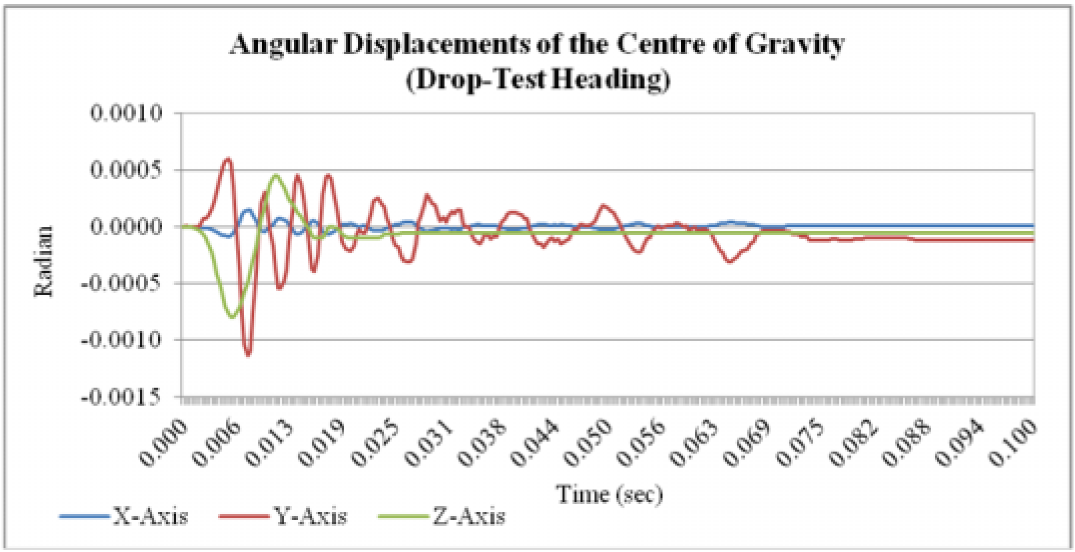


Figure 5.16: Angular displacements of the centre of gravity of brain from drop-test heading

Figure 5.17 shows the angular velocity of centre of gravity of brain from drop-test of sepak takraw ball for front-forehead heading. The maximum of the angular velocity is 0.0455 rad/s and the minimum is 0.0652 rad/s, both of them in y-axis.

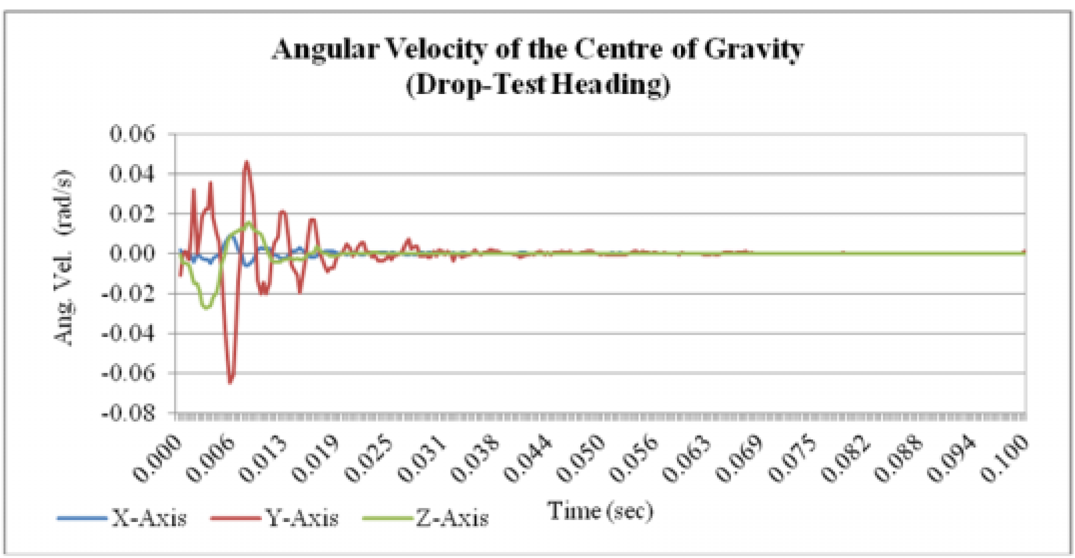


Figure 5.17: Angular velocity of centre of gravity of brain from drop-test heading

Lastly, Figure 5.18 shows the angular accelerations of the centre of gravity of brain from drop-test fall of sepak takraw ball for front-forehead heading. The maximum of angular acceleration is 13.55 rad/s^2 and minimum is -16.11 rad/s^2 in y-axis.

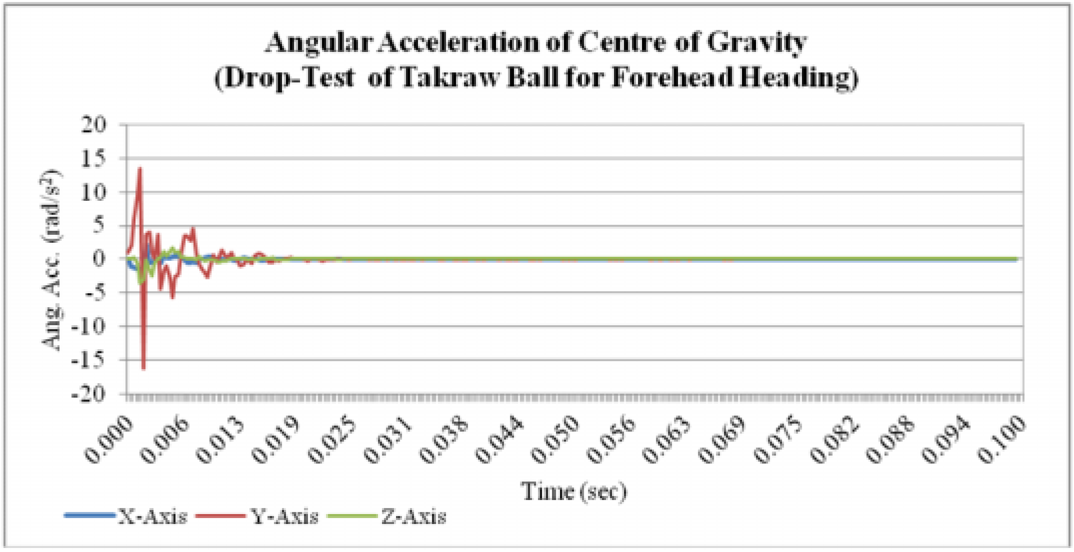


Figure 5.18: Angular accelerations of the centre of gravity of brain from drop-test heading

Based on the measurements above, the following HIC (refer to equation 2.2) and integration (refer to equation 2.4) for drop-test heading is calculated using following information.

$f(a)_{resultant}$ = 1262.911 m/s^2 a = 0 sec

$f(b)_{resultant}$ = 1144.505 m/s^2 b = 0.00033 sec

t_1 = 0 sec t_2 = 0.01089 sec

After the calculation from the equation above, the HIC was 87.507 for this study. Based on Newman et. al. (2000) figure in Figure 5.19, the HIC probability of concussion from the drop-test of sepak takraw ball heading is 13%.

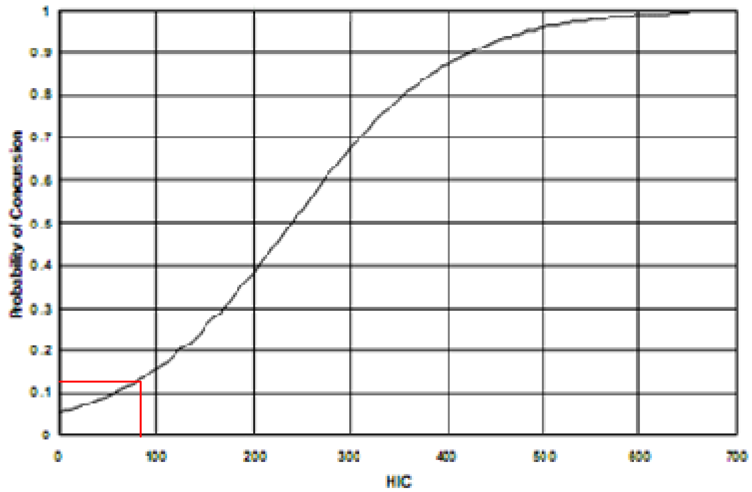


Figure 5.19: Probability of concussion based on HIC for drop of sepak takraw ball heading

Furthermore, based on the acceleration in the center of gravity of the brain, the angular accelerations and the contact time, the calculation for the HIP (refer to equation 2.8) for drop-test heading are calculated using following information.

C_1 = 4.5 kg	C_2 = 4.5 kg	C_3 = 4.5 kg
C_4 = 0.016 Nm/s^2	C_5 = 0.024 Nm/s^2	C_6 = 0.022 Nm/s^2
a_{x1} = 1176.7 m/s^2	a_{y1} = 1309.2 m/s^2	a_{z1} = 1151.6 m/s^2
a_{x2} = 1156.0 m/s^2	a_{y2} = 1226.9 m/s^2	a_{z2} = 1038.4 m/s^2
t_1 = 0 sec	t_2 = 0.00033 sec	
α_{x1} = 1.828 rad/s^2	α_{y1} = 13.548 rad/s^2	α_{z1} = 3.418 rad/s^2
α_{x2} = 2.168 rad/s^2	α_{y2} = 16.113 rad/s^2	α_{z2} = 2.916 rad/s^2

After calcultaion, the HIP is 6.221 kW. Based on Newman et. al. (2000) figure shown in Figure 5.20, the HIP probability of concussion is 10 % from the drop-test of sepak takraw ball heading.

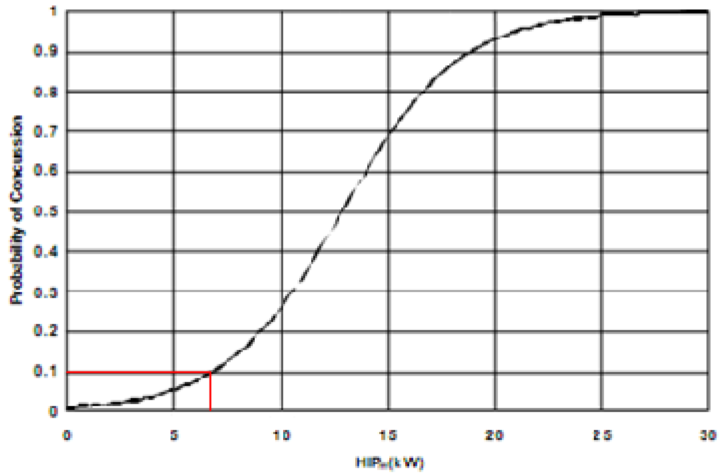


Figure 5.20: Probability of concussion based on HIP for drop of sepak takraw ball heading

5.3 FEA Result of Front-Forehead Heading

This section shows the result of the total impact force of the head, displacement of skull, displacement of whole brain, 6 points of displacement of frontal-brain and 6 points displacement of the occipital-brain of front-forehead heading.

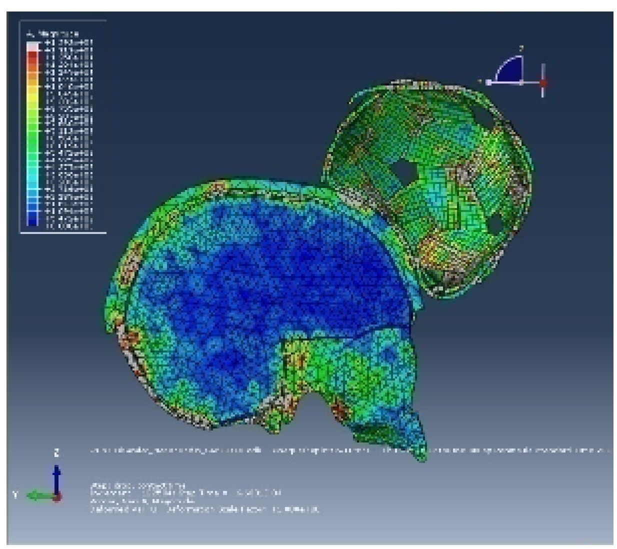


Figure 5.21: Finite element simulation of front-forehead heading

Figure 5.22 shows the contact time is 0.01023 sec (10.23 ms), and the maximum force on the head is 688.11 N. These were from the speed of sepak takraw ball before impact which is 13.58 m/s.

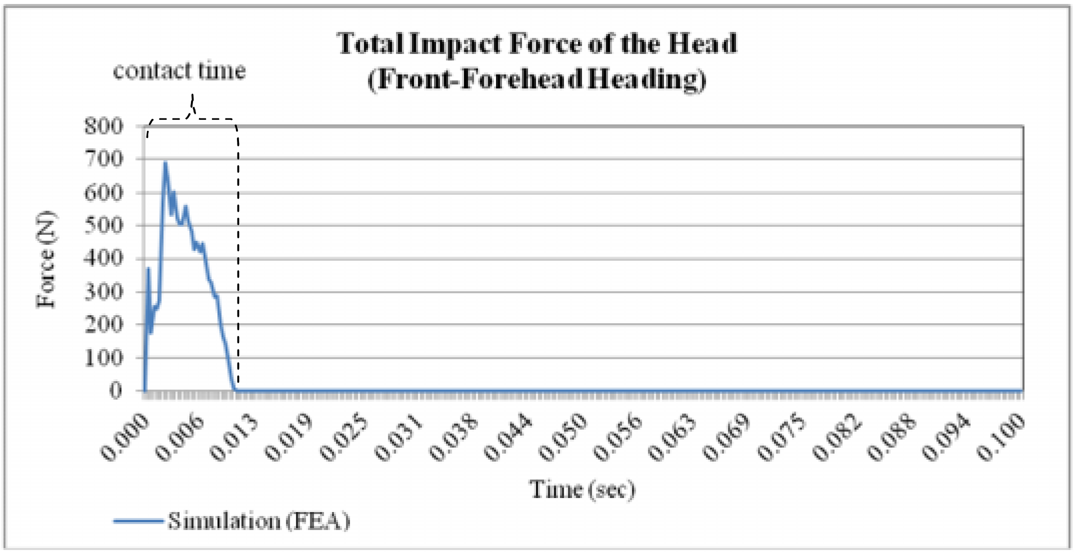


Figure 5.22: Total Impact force of the head at front-forehead heading

Figure 5.23 shows the displacement of skull at front-forehead heading. The maximum of displacement of skull during impact is 0.23 mm in y-axis and minimum is -0.058 mm . After impact at 100 ms of simulation, the displacement for x-axis is -0.0002 mm, for y-axis is -0.007 mm and z-axis is -0.0003 mm.

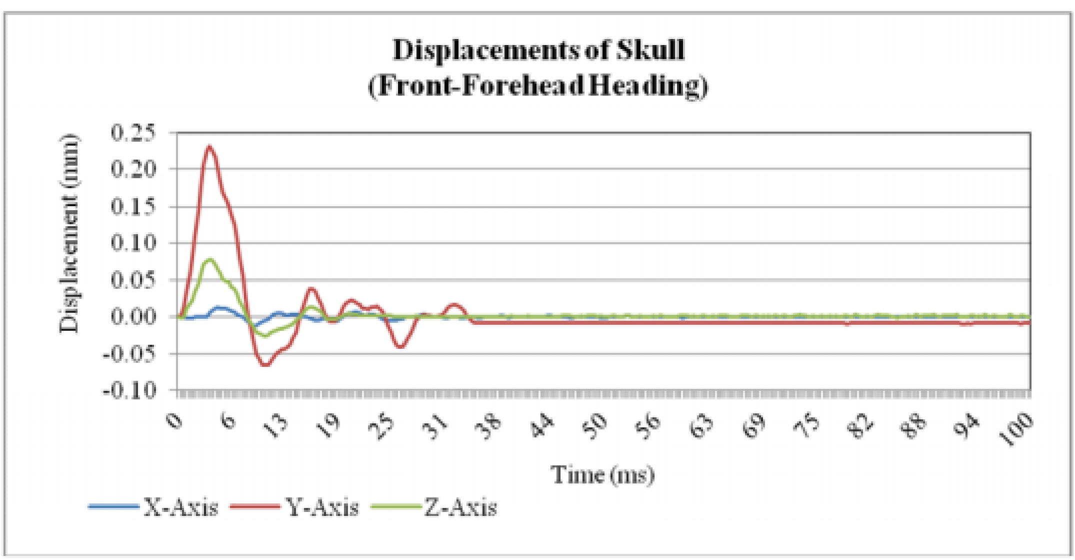


Figure 5.23: Displacement of skull at front-forehead heading

Figure 5.24 presents the average displacements of whole brain at front-forehead heading. The displacement of during impact maximum is 0.43 mm in y axis and the minimum is -0.19 mm in y-axis. After heading at 100 ms of simulation, the displacement for x-axis is 0.002 mm , for y-axis is -0.048 mm and z-axis is 0.006 mm.

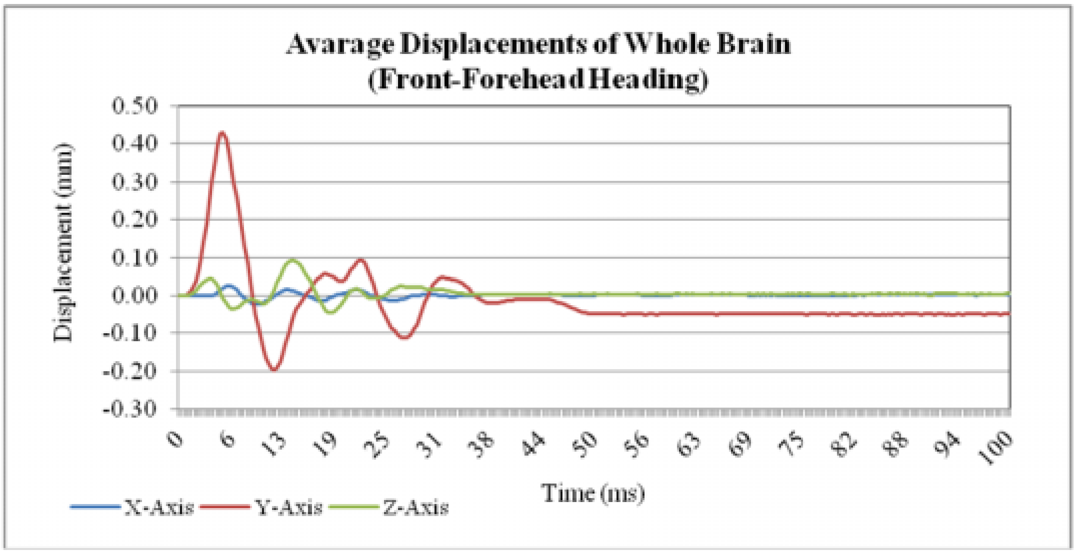


Figure 5.24: Average displacements of whole brain at front-forehead heading

Figure 5.25 presents the average acceleration of whole brain at front-forehead heading. The maximum magnitudes for positive and negative directions on the x-axis are 72.07 m/s^2 and -199.18 m/s^2. For y-axis, the maximum magnitudes for positive and negative directions are 104.36 m/s^2 and -196.84 m/s^2. As for z-axis, the maximum magnitudes of positive and negative directions are 140.69 m/s^2 and -91.76 m/s^2.

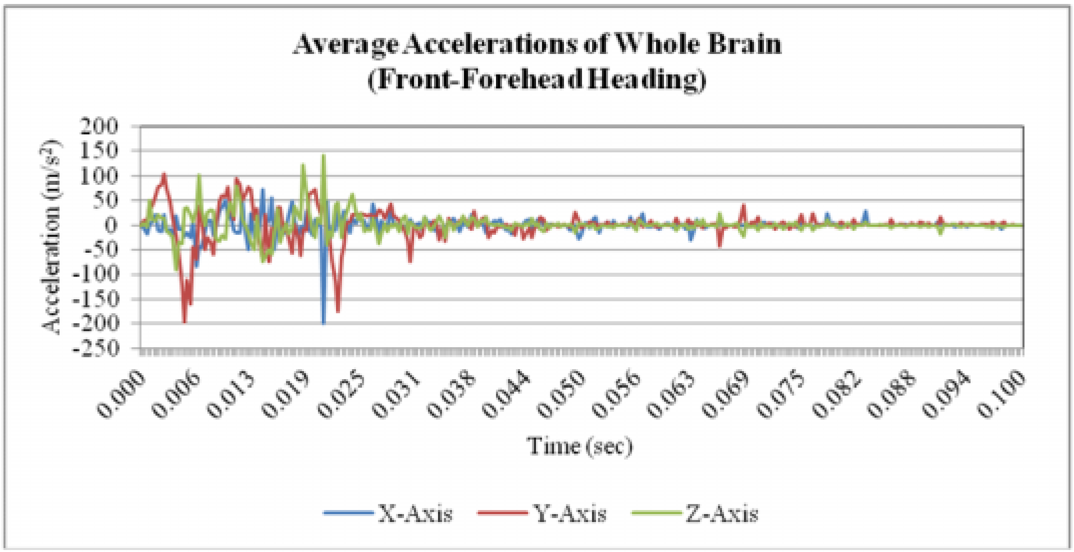


Figure 5.25: Average acceleration of whole brain at front-forehead heading

Figure 5.26 shows displacements of the frontal-brain in the x-axis direction on front-forehead heading. Then, the maximum displacement 0.058 mm and the minimum -0.053 mm, both of them at point 1. The displacement of after impact at 100 ms of simulation for point 1 is 0.010 mm, point 2 is 0.002 mm, point 3 is 0.004 mm, point 4 is 0.004 mm, point 5 is 0.001 mm and point 6 is -0.0001 mm.

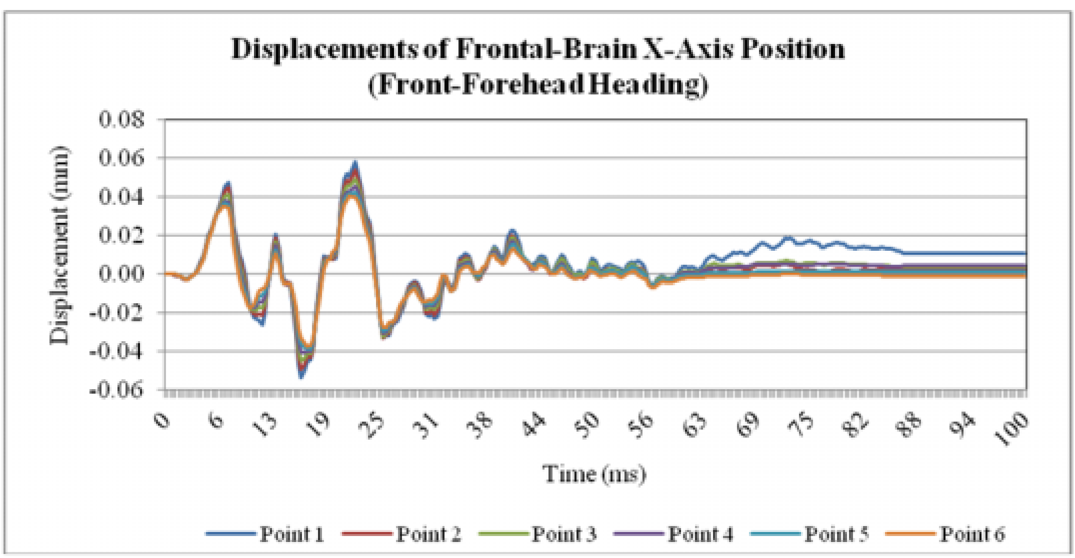


Figure 5.26: Displacements of frontal-brain x-axis direction on front-forehead heading

Figure 5.27 shows the displacements of the frontal-brain in the y-axis direction on front-forehead heading. The maximum of displacements during impact is 0.715 mm in point 1 and the minumum is -0.387 mm in point 6. Then, the displacements after impact at 100 ms of simulation for point 1 is -0.139 mm, point 2 is -0.106 mm, point 3 is -0.104 mm, point 4 is -0.104 mm, point 5 is -0.100 mm and point 6 is -0.080 mm.

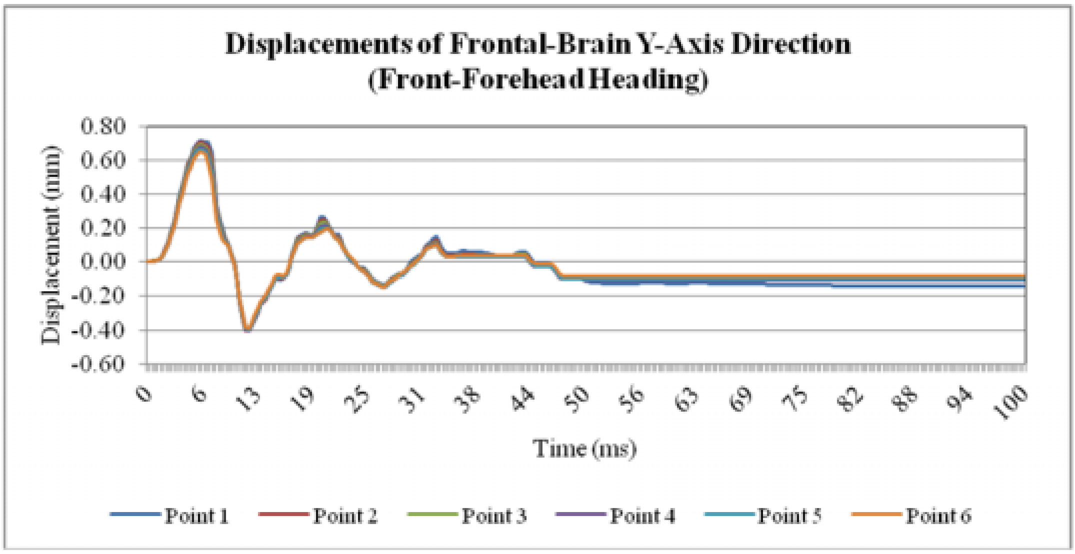


Figure 5.27: Displacements frontal-brain y-axis direction on front-forehead heading

Figure 5.28 shows the displacements of the frontal-brain in the z-axis direction on front-forehead heading. Then, the maximum displacement during impacts is 0.462 mm and the minimum is -0.276 mm, both of them at point 1. The displacement after impact at 100 ms of simulation for point 1 is -0.002 mm, point 2 is -0.096 mm, point 3 is -0.106 mm, point 4 is -0.109 mm, point 5 is -0.113 mm and point 6 is -0.145 mm.

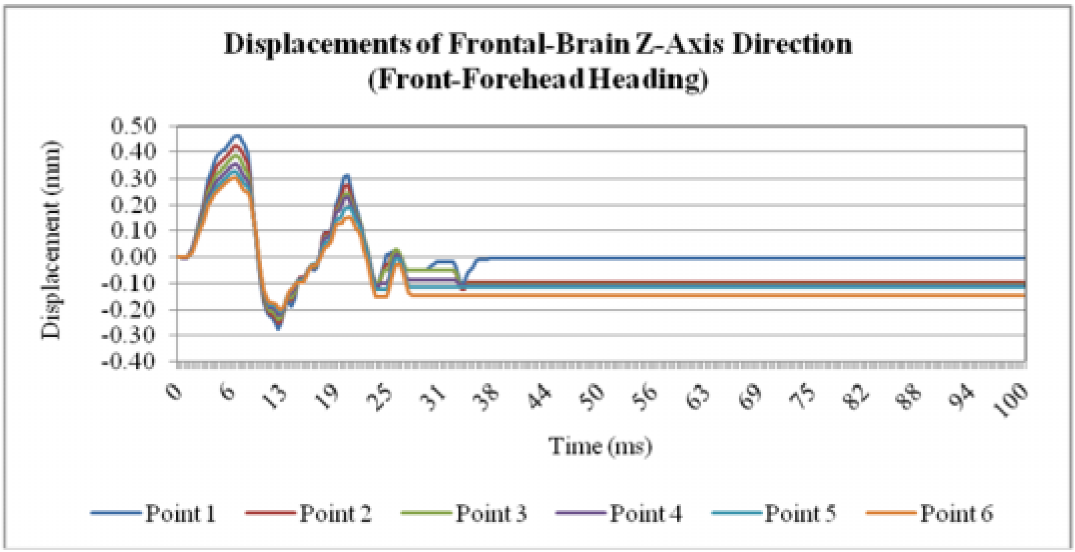


Figure 5.28: Displacements of frontal-brain z-axis direction on front-forehead heading

Figure 5.29 shows the displacements of the occipital-brain in the x-axis direction on front-forehead heading. Then, the maximum diplacements during impact is 0.052 mm an the minimum -0.055 mm, both of them at point 1. Afterward, the displacement after impact at 100 ms of simulation for point 1 is -0.006 mm, point 2 is -0.002 mm, point 3 is -0.001 mm, point 4 is -0.002 mm, point 5 is 0.004 mm and point 6 is 0.006 mm.

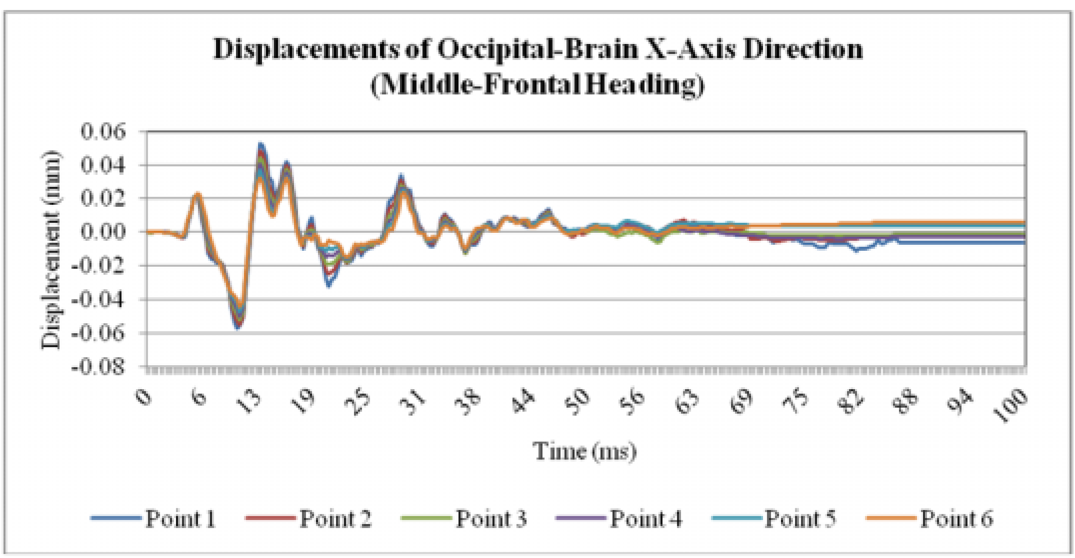


Figure 5.29: Displacements of occipital-brain x-axis direction on front-forehead heading

Figure 5.30 presents the displacements of the occipital-brain in the y-axis direction on front-forehead heading. The maximum of displacement during impact is 0.443 mm in point 6 and the minimun is -0.255 mm in point 1. Then, the displacement after impact after 100 ms of simulation for point 1 is -0.071 mm, point 2 is -0.058 mm, point 3 is -0.064 mm, point 4 is -0.062 mm, point 5 is -0.063 mm and point 6 is -0.073 mm.

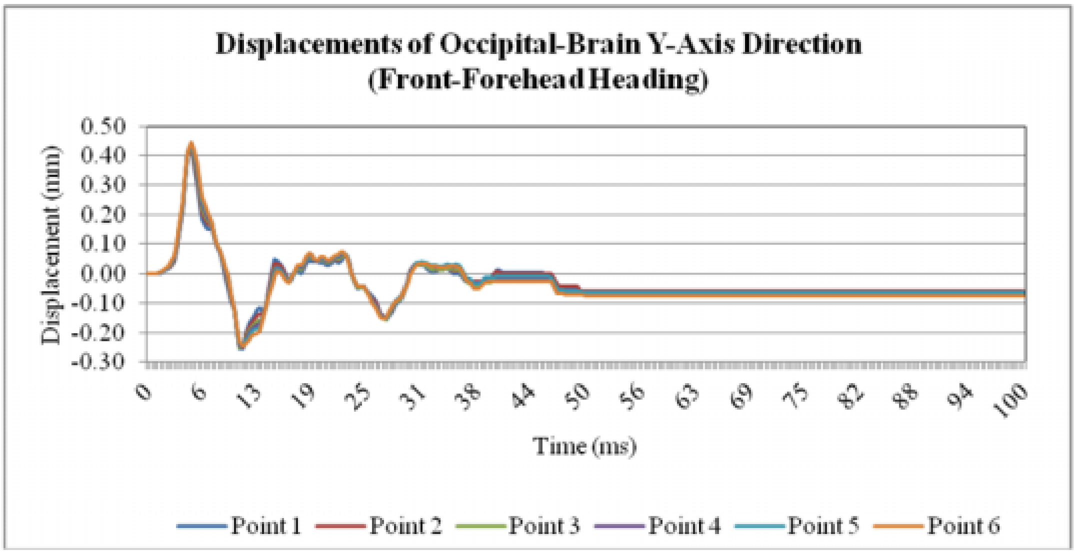


Figure 5.30: Displacements of occipital-brain y-axis direction on front-forehead heading

Figure 5.31 presents the displacements of the occipital-brain in the z-axis direction during front-forehead heading. The maximum of displacement during impact is 0.777 mm and the minimum is -0.519 mm, both of them at point 1. Then, the displacement after impact at 100 ms of simulation for point 1 is -0.107 mm, point 2 is -0.093 mm, point 3 is -0.117 mm, point 4 is -0.080 mm, point 5 is -0.025 mm and point 6 is 0.001 mm.

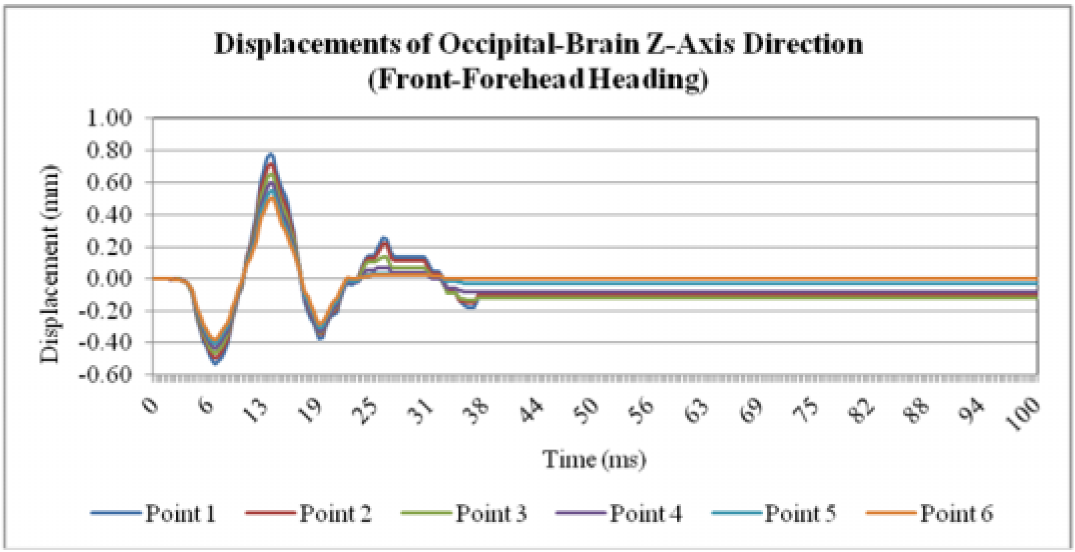


Figure 5.31: Displacements of occipital-brain z-axis direction on front-forehead heading

5.3.1 Result of Validation for Front-forehead heading

This section presents the result of validation for front-forehead heading. The results are compared between the experiment from the championship and the simulation.

The comparison of speed of the centre of sepak takraw ball for front-forehead heading from FEA simulation and experiment is shown in Figure 5.32, where the difference is 4.9%.

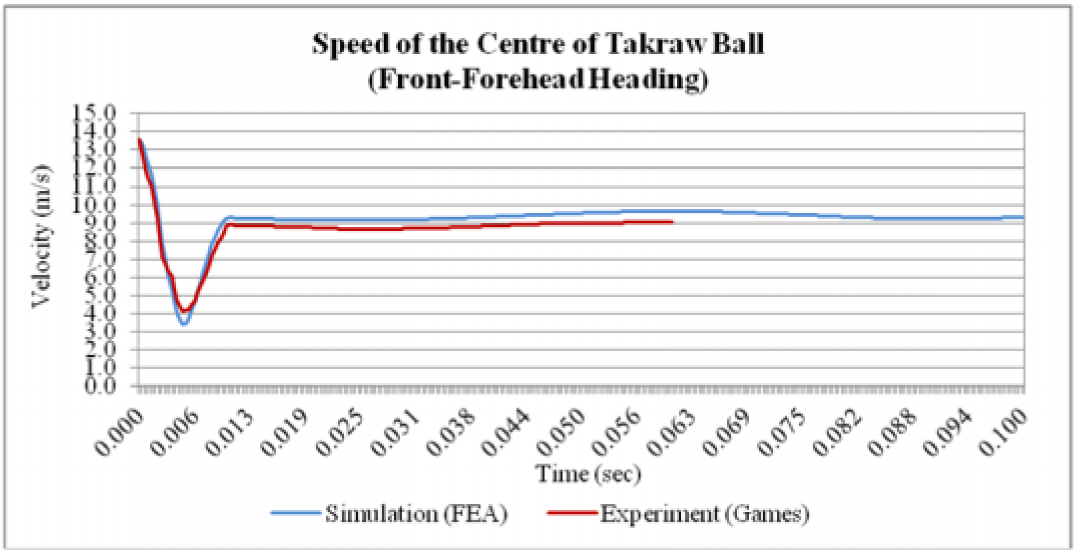
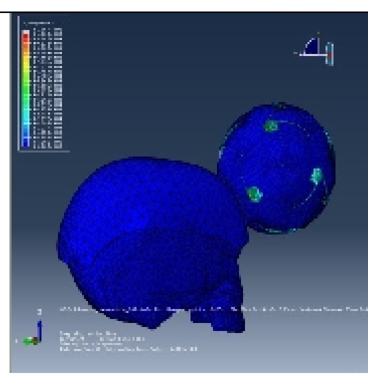
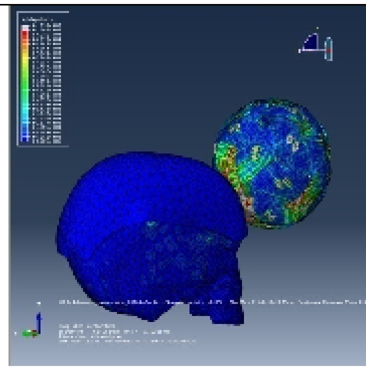
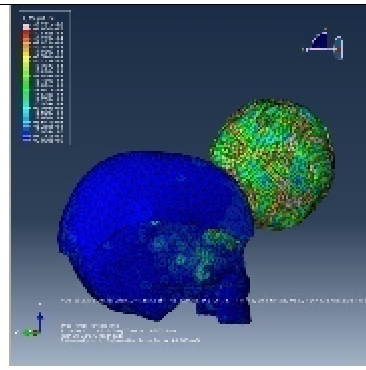
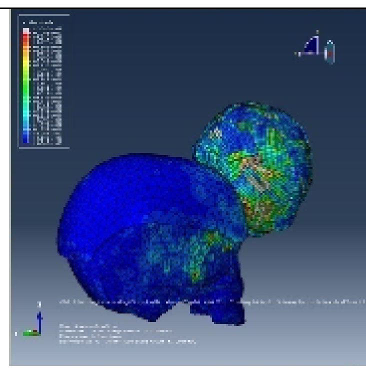
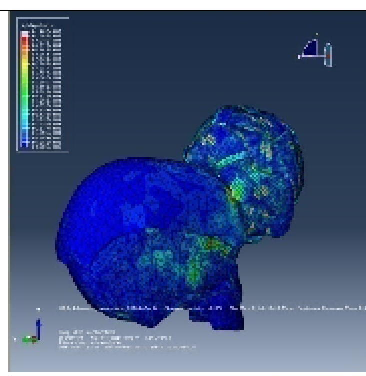


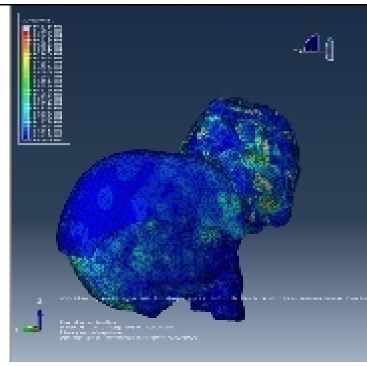
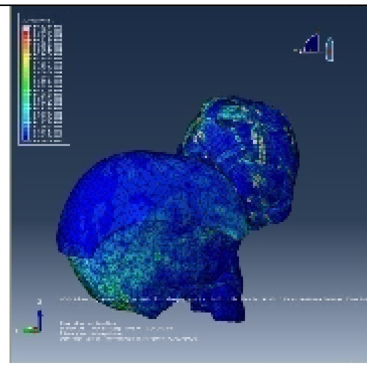
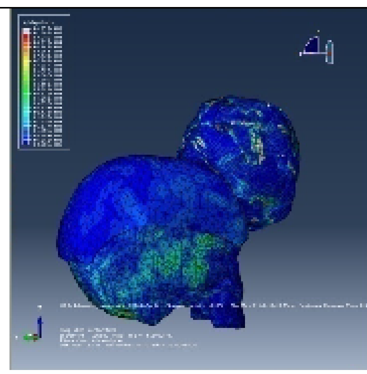
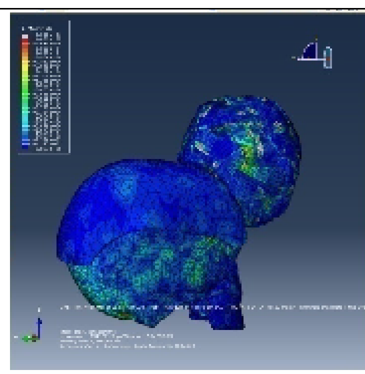
Figure 5.32: Comparison of speed of the centre of sepak takraw ball for front-forehead heading

Table 5.2 display the comparative images between FEA simulation and the results from experiment which used the high speed camera for the front-forehead heading. The difference of contact time is found to be 7% between both of them.

Table 5.2: Comparison of picture between FEA simulation and high speed camera data for middle frontal heading

Time (ms)	FE Simulation	High Speed Camera
(0.0) Before heading		

1 first time of front-forehead heading		
2		
3		
4		

5		
6		
7		
8		

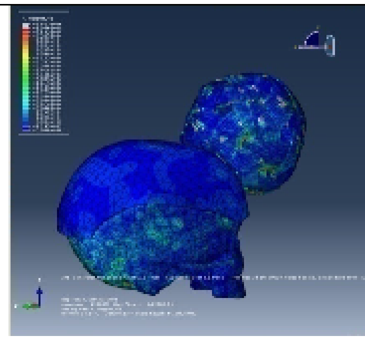
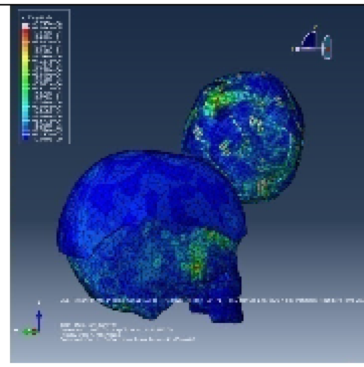
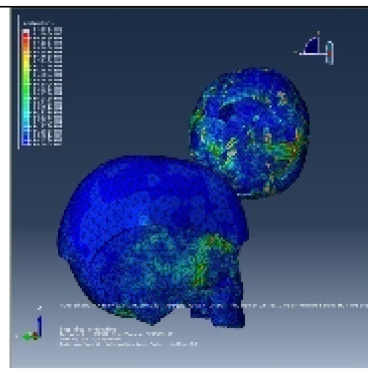
9		
10		
End of front-forehead heading		
	The time is 10.23 ms	The time is 11.00 ms

Table 5.2 shows the difference of contact time is 7 % between simulation (FEA) and experiment (Games).

5.3.2 Head Injury Criterion and Head Impact Power of Front-Forehead Heading

This section presents the head injury criterion (HIC) and the head impact power (HIP) of front-forehead heading. For the calculation of HIC, the acceleration at the centre of gravity (*a*) and contact time (*t*) of the heading are required. Figure 5.33 is the

FE simulation graph of the brain during front-forehead heading. It shows that the maximum displacement is 0.459 mm and the minimum is -0.228 mm in y-axis. After the impact, the displacements are 0.0008 mm for the x-axis, 0.0824 mm for the y-axis and 0.0247 mm for the z-axis.

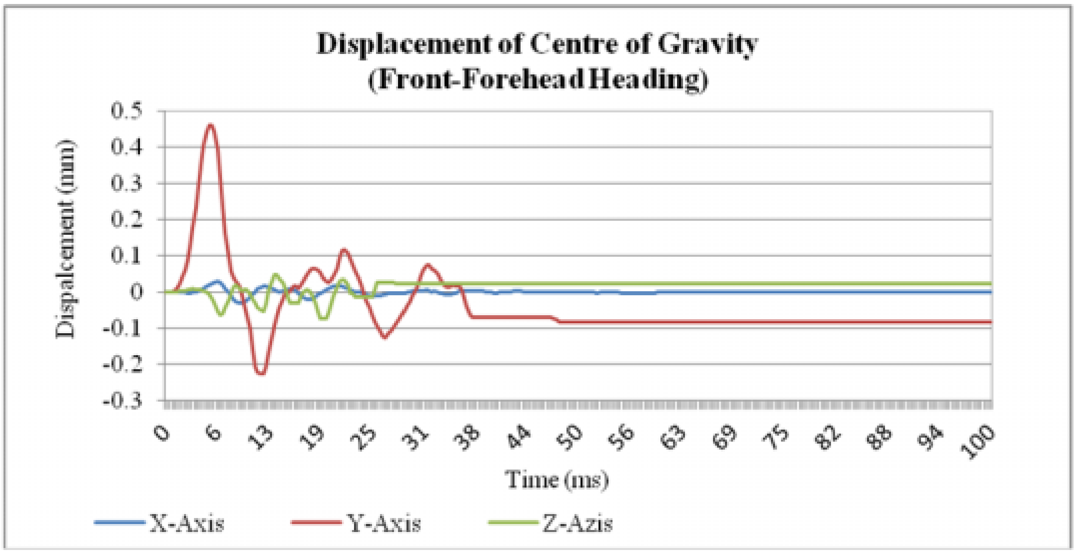


Figure 5.33: Displacement of the centre of gravity of brain for front-forehead heading

Figure 5.34 shows the velocity of the centre of gravity of the brain during front-forehead heading. The maximum of velocity is 0.168 m/s and the minimum is -0.236 m/s in the y-axis.

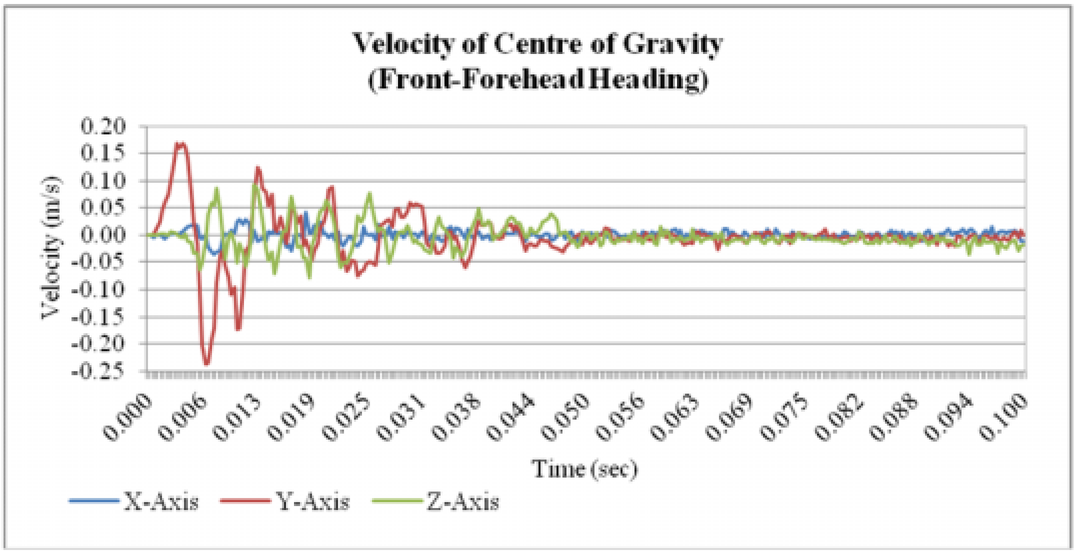


Figure 5.34: Velocity of the centre of gravity of brain for front-forehead heading

Figure 5.35 displays the acceleration of the centre of gravity of the brain during front-forehead heading. It shows that the maximum magnitudes for positive and negative directions in x-axis are 1667.8 m/s^2 and -1358.6 m/s^2. The maximum magnitudes for positive and negative directions in y-axis are 1674.5 m/s^2 and -1462.1 m/s^2. And finally in the z-axis are 1591.5 m/s^2 and -1543.3 m/s^2.

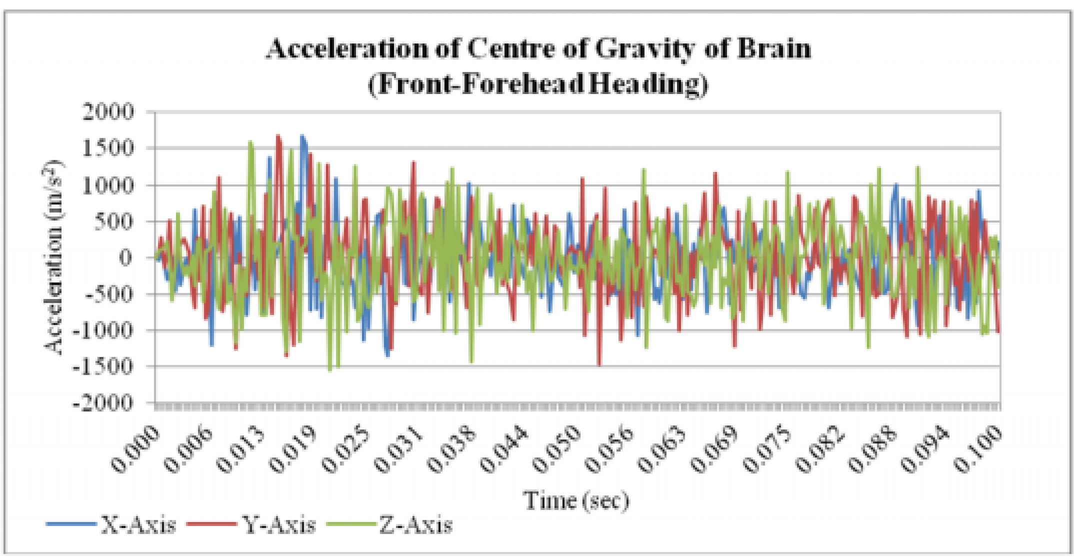


Figure 5.35: Acceleration of centre of gravity of brain for front-forehead heading

Figure 5.36 shows the angular displacement of the centre of gravity of the brain during front forehead heading. The maximum angular displacement is 0.0065 rad and the minimum is -0.0033 rad both of them in z-axis.

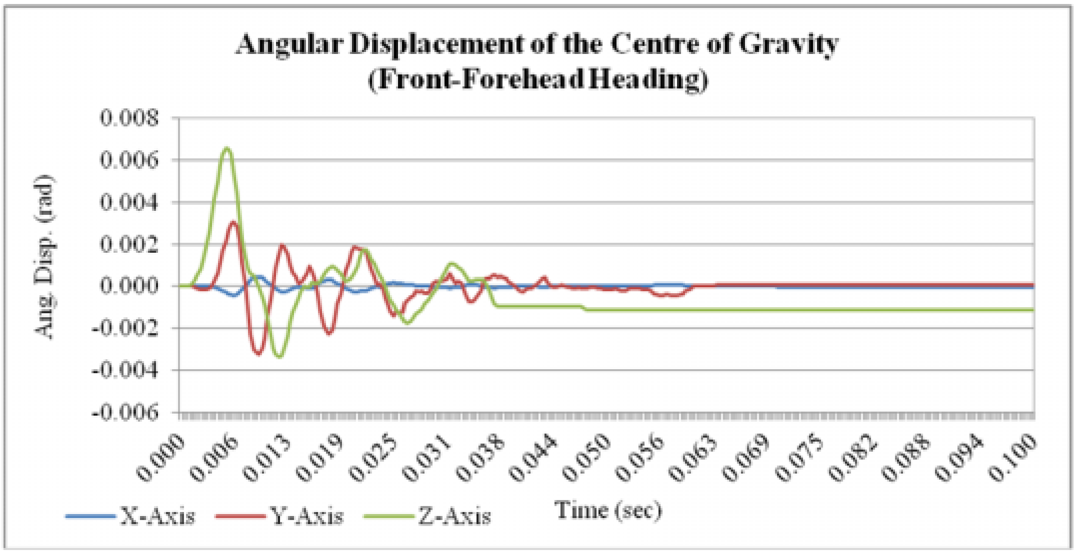


Figure 5.36: Angular displacement of centre of gravity of brain for front-forehead heading

Figure 5.37 shows the angular velocity of the centre of gravity of the brain during front-forehead heading. The maximum of angular velocity is 0.246 rad/s and the minimum is - 0.179 rad/s, both of them in z-axis.

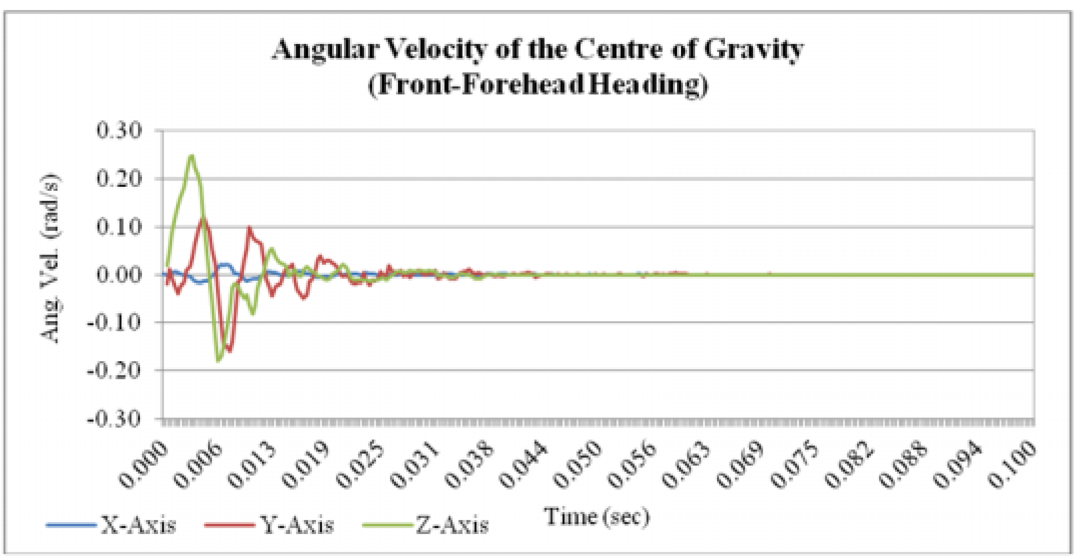


Figure 5.37: Angular velocity of centre of gravity of brain for front-forehead heading

The result of the angular acceleration of the centre of gravity of the brain during the front-forehead heading is shown in Figure 5.38. The maximum angular acceleration is 12.97 rad/s^2 and the minimum is -15.27 rad/s^2, both of them in z-axis.

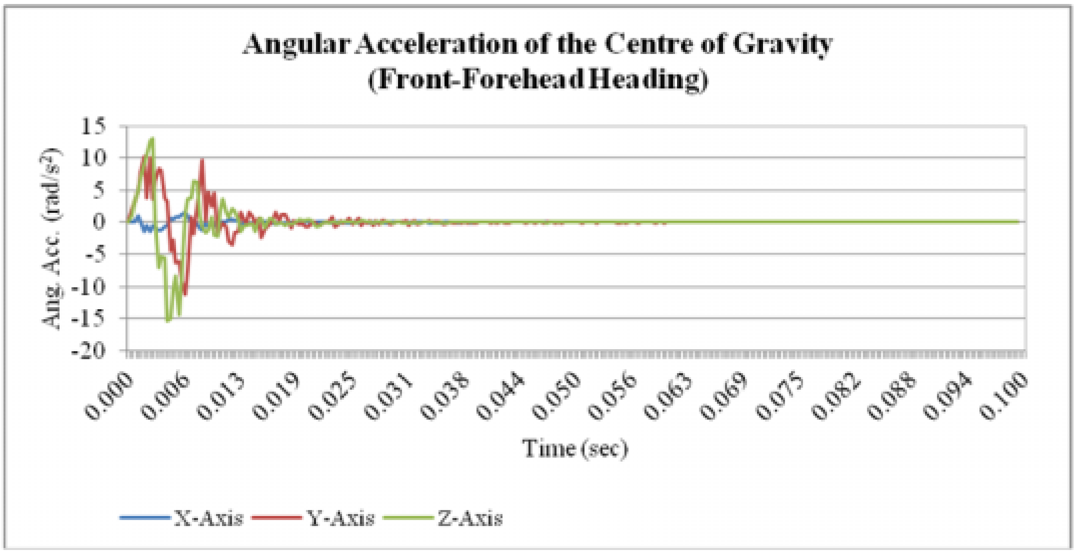


Figure 5.38: Angular acceleration of centre of gravity of brain for front-forehead heading

Based on the measurements above, the following HIC (refer to equation 2.2) and integration (refer to equation 2.4) for front-forehead is calculated using following information.

$f(a)_{resultant}$ = 1689.4 m/s^2	a = 0 sec
$f(b)_{resultant}$ = 1604.3 m/s^2	b = 0.00033 sec
t_1 = 0 sec	t_2 = 0.01023 sec

The HIC is found to be 210.158 with a speed of 13.581 m/s of the sepak takraw ball. Based on Newman et. al. (2000) as shown in Figure 5.39, the probability of concussion is estimated as 42 % (red line) for front- forehead heading.

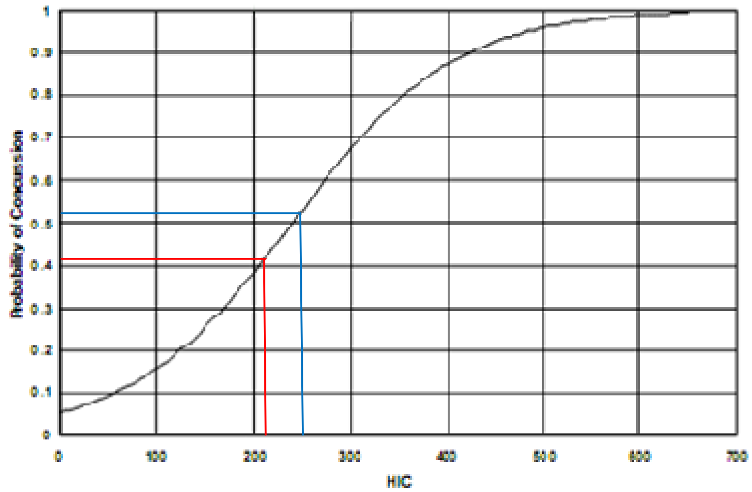


Figure 5.39: Probability of concussion based on HIC for front-forehead heading

Figure 5.40 shows the HIC of front-forehead heading at different speeds of the sepak takraw ball before impact at 5, 10, 13.581 and 15 m/s. At the maximum speed of 15 m/s, the HIC is 252.189 with a 52 % (blue line) probability of concussion (see Figure 5.39).

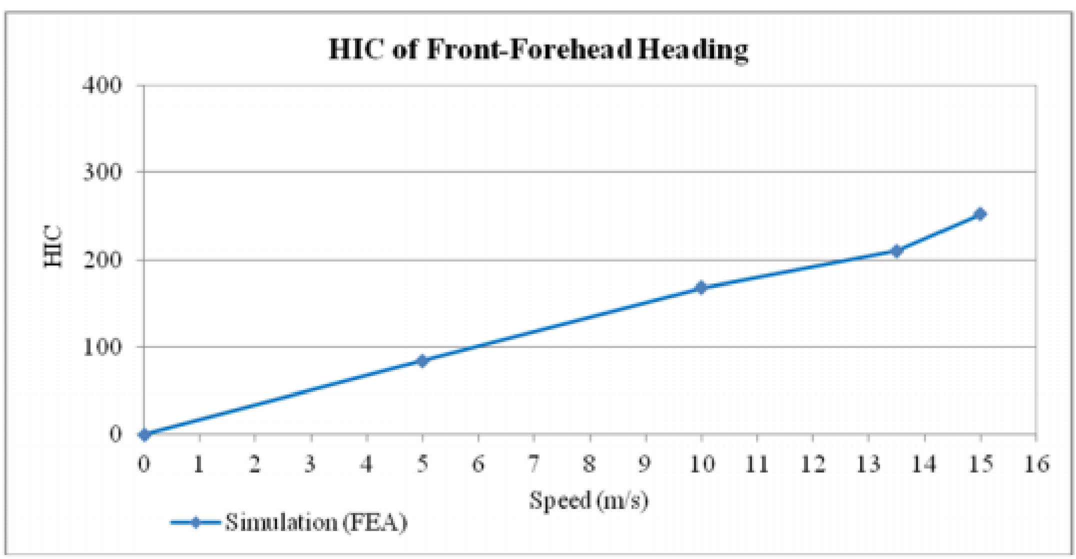


Figure 5.40: HIC of front-forehead heading with varieties of speed of sepak takraw ball

Subsequently, the following HIP (refer to equation 2.8) for front-forehead heading are calculated using following information.

$C_1 = 4.5$ kg $\quad C_2 = 4.5$ kg $\quad C_3 = 4.5$ kg

$C_4 = 0.016$ Nm/s^2 $\quad C_5 = 0.024$ Nm/s^2 $\quad C_6 = 0.022$ Nm/s^2

$a_{x1} = 1667.8$ m/s^2 $\quad a_{y1} = 1674.5$ m/s^2 $\quad a_{z1} = 1591.5$ m/s^2

$a_{x2} = 1551.1$ m/s^2 $\quad a_{y2} = 1572.7$ m/s^2 $\quad a_{z2} = 1472.7$ m/s^2

$t_1 = 0$ sec $\quad t_2 = 0.00033$ sec

$\alpha_{x1} = 1.536$ rad/s^2 $\quad \alpha_{y1} = 11.239$ rad/s^2 $\quad \alpha_{z1} = 15.266$ rad/s^2

$\alpha_{x2} = 1.296$ rad/s^2 $\quad \alpha_{y2} = 9.207$ rad/s^2 $\quad \alpha_{z2} = 14.909$ rad/s^2

The HIP is found to be 11.366 kW at a speed of 13.581 m/s of the sepak takraw ball. Based on Newman et. al. (2000), Figure 5.41 shows that the HIP probability of concussion is 39 % (red line) and for speed 15 m/s the HIP is 49 % for front- forehead heading (blue line).

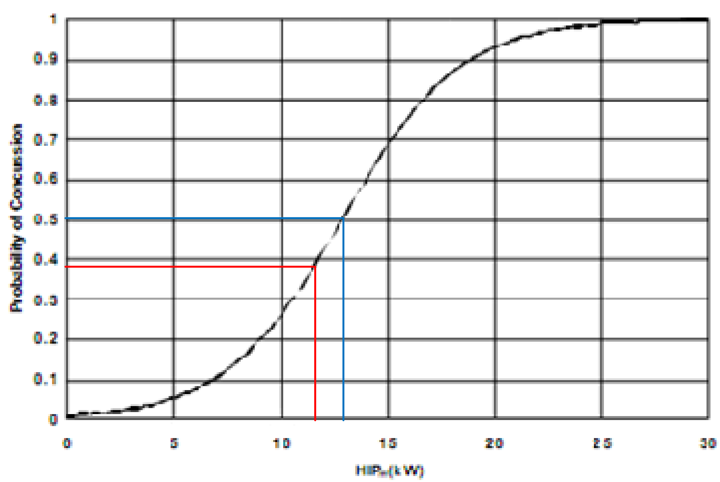


Figure 5.41: Probability of concussion based on HIP for front-forehead heading

Figure 5.42 shows the HIP of front-forehead heading at different speeds of the sepak takraw ball before impact of 5, 10, 13.58 and 15 m/s. The maximum HIP of the sepak takraw ball is 13.63 kW at a speed of 15 m/s with a 51 % probabilty of concussion (see Figure 5.41).

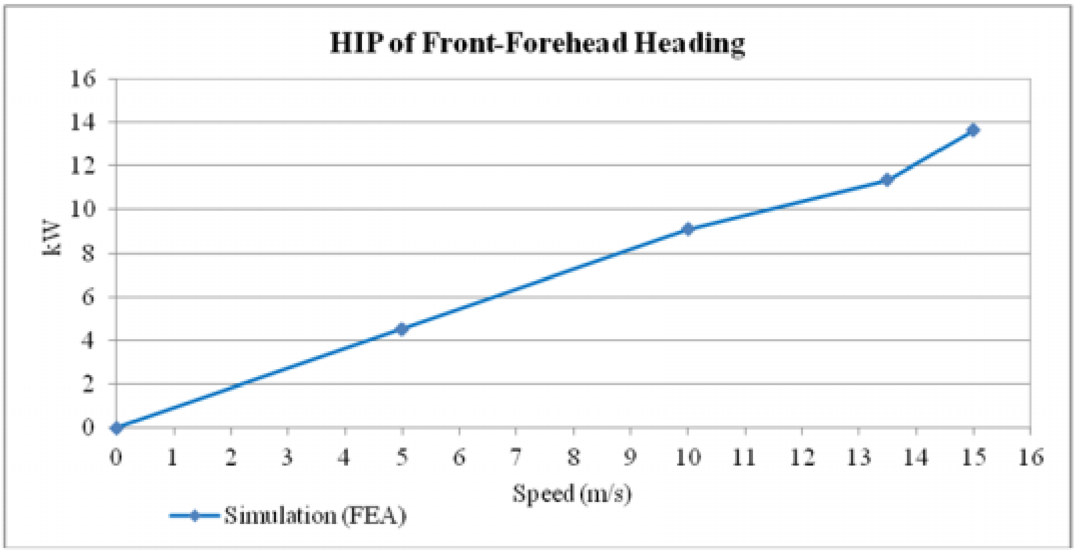


Figure 5.42: HIP of front-forehead heading with varieties of speed of sepak takraw ball

5.4 FEA Result of Top-Forehead Heading

This section presents the result of the total impact force on the head, displacement of skull, and displacement of whole brain, 6 points displacements of the frontal-brain and 6 points displacements of the occipital-brain of top-forehead heading. Figure 5.43 shows the finite element simulation of top-forehead heading.

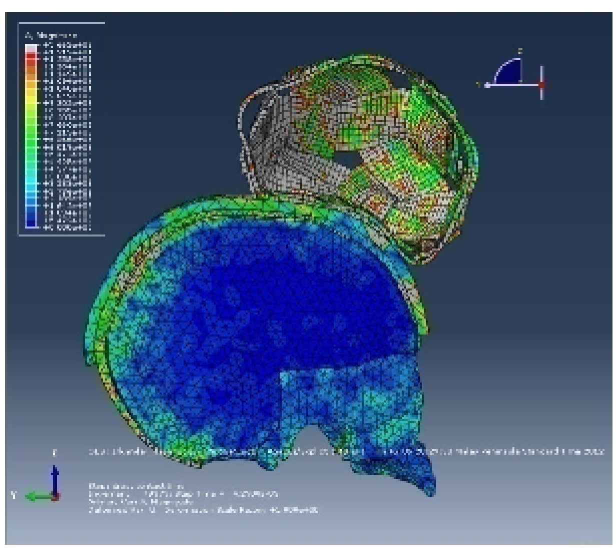


Figure 5.43: Finite element simulation of top-forehead heading

The total impact force on the head during top-forehead heading is shown in Figure 5.44. The maximum impact force is 672.41 N and the contact time is 10.23 ms at an impact speed of 13.58 m/s.

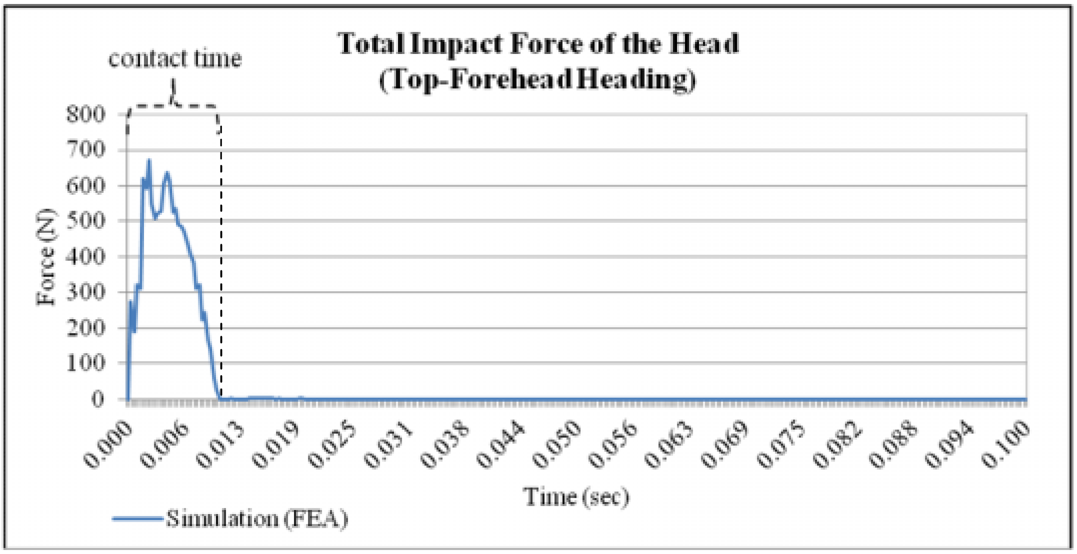


Figure 5.44: Total impact force of the head on top-forehead heading

The average displacement of the skull on top-forehead heading is illustrated in Figure 5.45., It shows that the maximum displacement during impact is 0.061 mm and the minimum is -0.055 mm, both of them in y-axis. Then, the displacement after impact at 100 ms of simulation in the x-axis is 0.001 mm, y-axis is -0.009 mm and z-axis is 0.0009 mm.

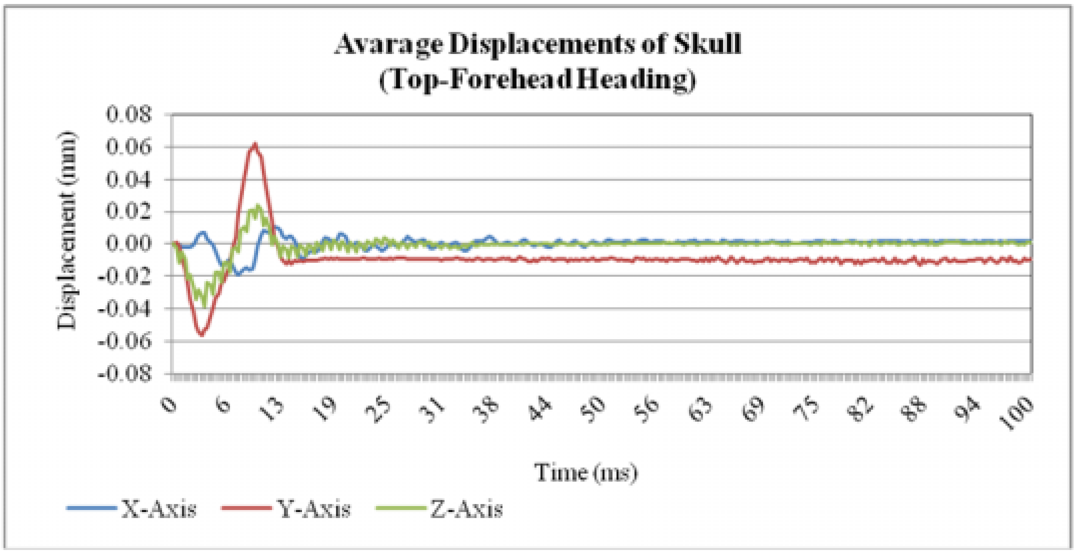


Figure 5.45: Average displacements of the skull on top-forehead heading

Figure 5.46 presents the average displacements of the whole brain during top-forehead heading. It shows that the maximum of displacements during impact is 0.111 mm and the minimum -0.101 mm, both of them in y-axis. Then, displacements after impact at 100 ms of simulation in the x-axis is 0.006 mm, y-axis is -0.017 mm and z-axis is 0.003 mm.

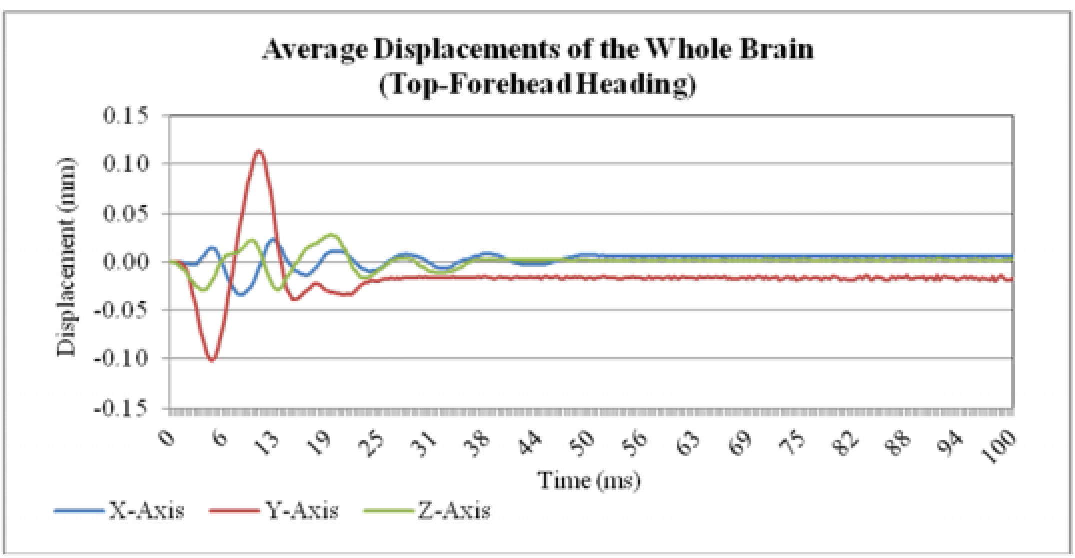


Figure 5.46: Average displacements of whole brain on top-forehead heading

Figure 5.47 shows the average accelerations of the whole brain during top-forehead heading. The the maximum magnitude for positive and negative directions in x-axis are 32.88 m/s^2 and -73.15 m/s^2. The maximum magnitudes for positive and negative directions in y-axis are 62.28 m/s^2 and -78.66 m/s^2. The finally in the z-axis are 68.31 m/s^2 and -37.39 m/s^2.

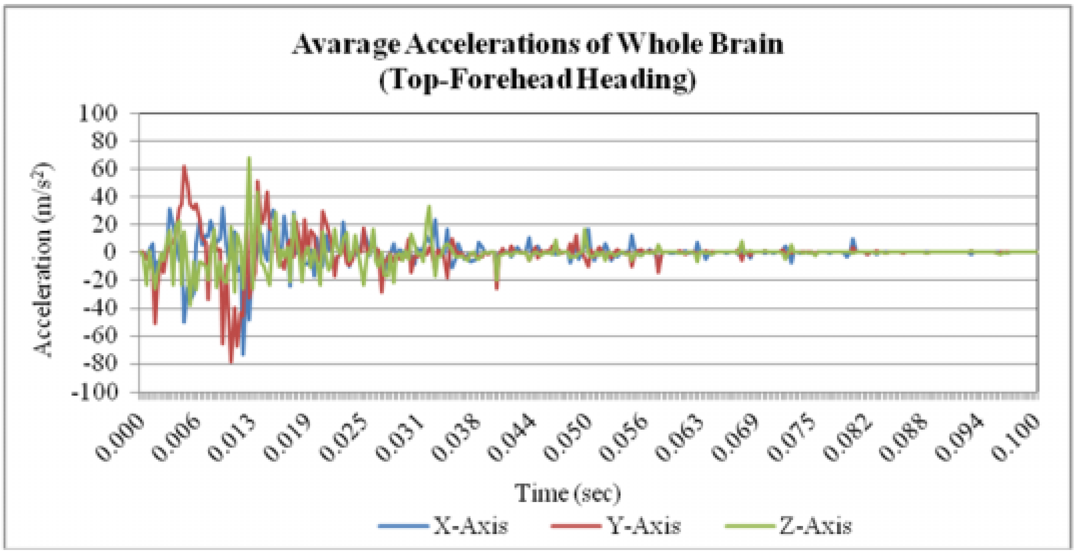


Figure 5.47: Average Accelerations of whole brain on top-forehead heading

Figure 5.48 presents the displacements of the frontal-brain in the x-axis direction during top-forehead heading. It shows that the maximum displacement during impact is 0.426 mm and the minimum of displacement is -0.463 mm, both of them at point 1. Then, the displacements after impact at 100 ms of simulation for point 1 is 0.003 mm, point 2 is 0.004 mm, point 3 is 0.004 mm, point 4 is -0.002 mm, point 5 is -0.002 mm and point 6 is 0.0001 mm.

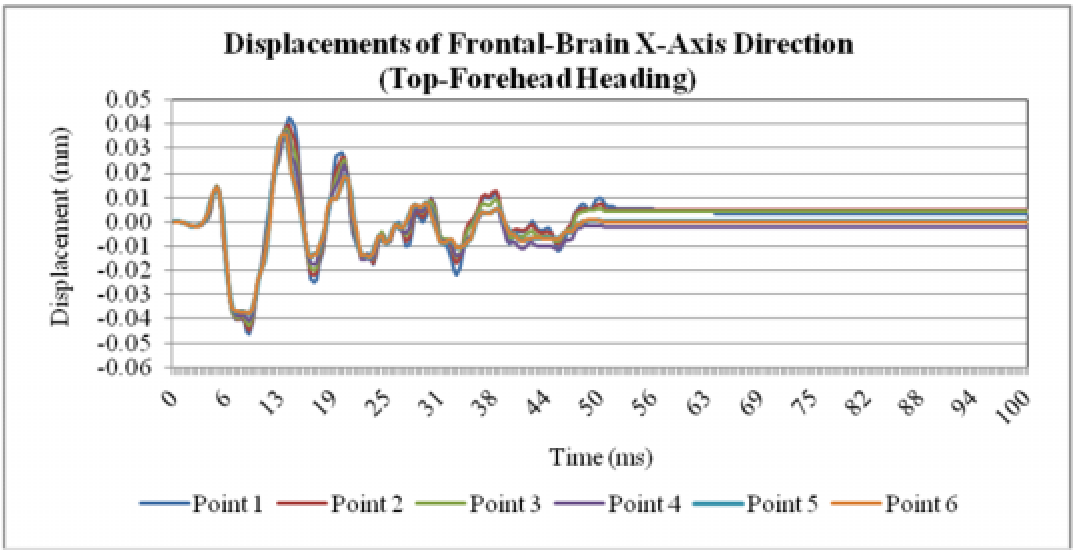


Figure 5.48: Displacements of frontal-brain x-axis direction on top-forehead heading

Figure 5.49 illustrates the displacements of the frontal-brain in the y-axis direction during top-forehead heading. The maximum displacement during impact is 0.203 mm and the minimum is -0.149 mm, both of them at point 1. Then, the displacements after impact at 100 ms in simulation for point 1 is 0.089 mm, point 2 is 0.092 mm, point 3 is 0.068 mm, point 4 is 0.022 mm, point 5 is -0.012 mm and point 6 is -0.041 mm.

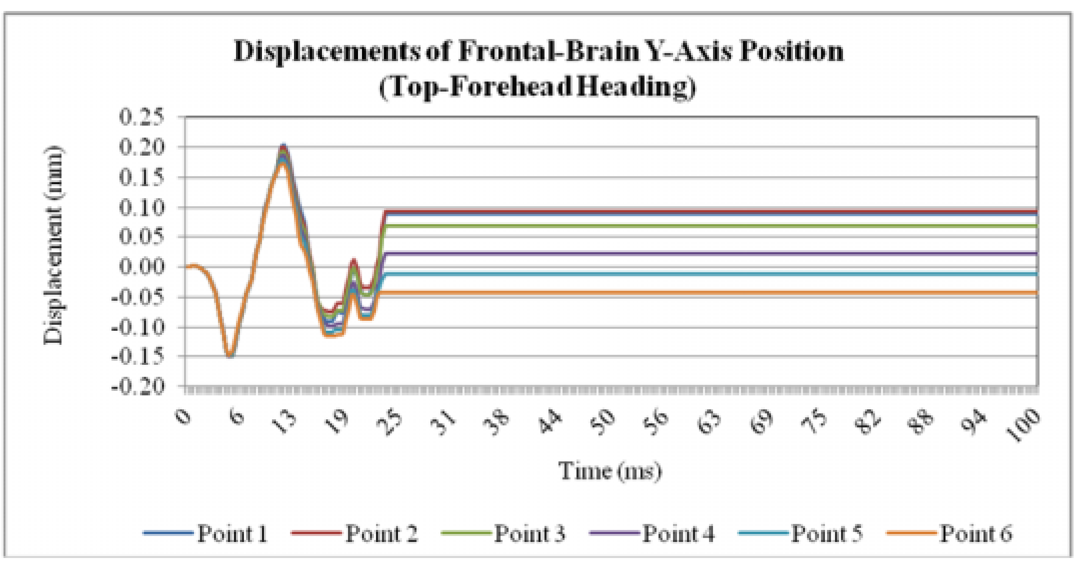


Figure 5.49: Displacements of frontal-brain y-axis direction on top-forehead heading

Figure 5.50 displays the displacements of the frontal-brain in the z-axis direction during top-forehead heading. The maximum displacement during impact is 0.153 mm and the minimum is -0.110 mm, both of them at point 1. The displacements after impact at 100 sec in simulation for point 1 is 0.035 mm, point 2 is 0.033 mm, point 3 is 0.039 mm, point 4 is 0.027 mm, point 5 is 0.008 mm and point 6 is 0.005 mm.

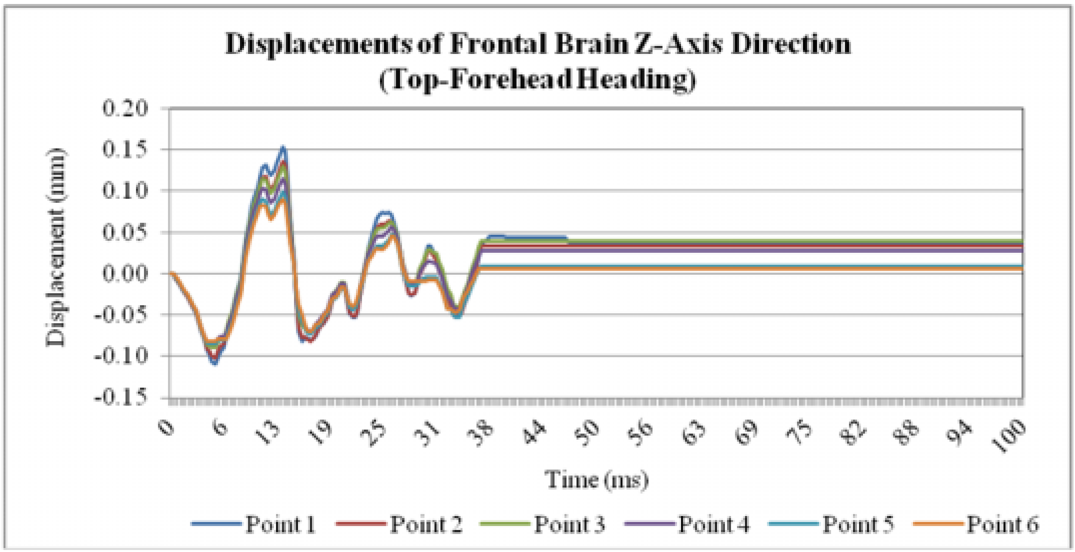


Figure 5.50: Displacements of frontal-brain z-axis direction on top-forehead heading

Figure 5.51 shows the displacements of the occipital-brain in the x-axis direction during top-forehead heading. The maximum displacement of the occipital-brain in the x-axis direction of top-forehead heading during impact is 0.031 mm and the minimum is -0.044 mm, both of them at point 1.The displacement after impact at 100 ms from simulation for point 1 is 0.016 mm, point 2 is 0.006 mm, point 3 is 0.011 mm, point 4 is 0.007 mm, point 5 is 0.007 mm and point 6 is 0.008 mm.

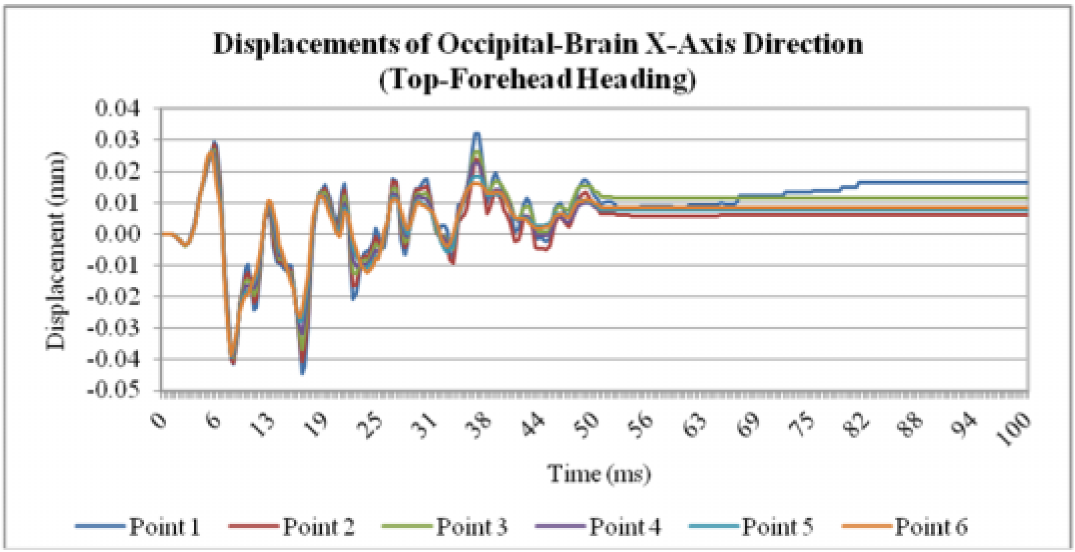


Figure 5.51: Displacements of occipital-brain x-axis direction on top-forehead heading

Figure 5.52 shows the displacements of the occipital-brain in the y-axis direction during top-forehead heading. The maximum displacement during impact is 0.110 mm and the minimum is -0.100 mm, both of them at point 6. Then, the displacements after impact at 100 ms of simulation for point 1 is -0.038 mm, point 2 is -0.054 mm, point 3 is -0.056 mm, point 4 is -0.064 mm, point 5 is -0.060 mm and point 6 is -0.052 mm.

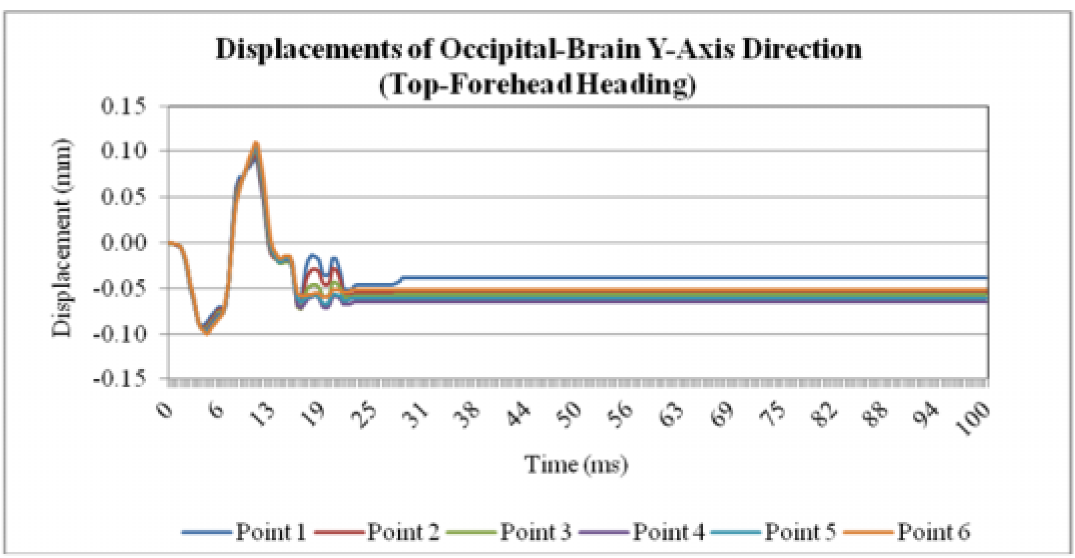


Figure 5.52: Displacements of occipital-brain y-axis direction on top-forehead heading

Figure 5.53 shows displacements of the occipital-brain in the z-axis direction on top-forehead heading. The maximum of displacement during impact is 0.242 mm and the minimum is -0.196 mm, both of them at point 1. Then, the displacements after impacts at 100 ms of simulation for point 1 is -0.025 mm, point 2 is -0.024 mm, point 3 is -0.035 mm, point 4 is -0.035 mm, point 5 is -0.023 mm and point 6 is -0.020 mm.

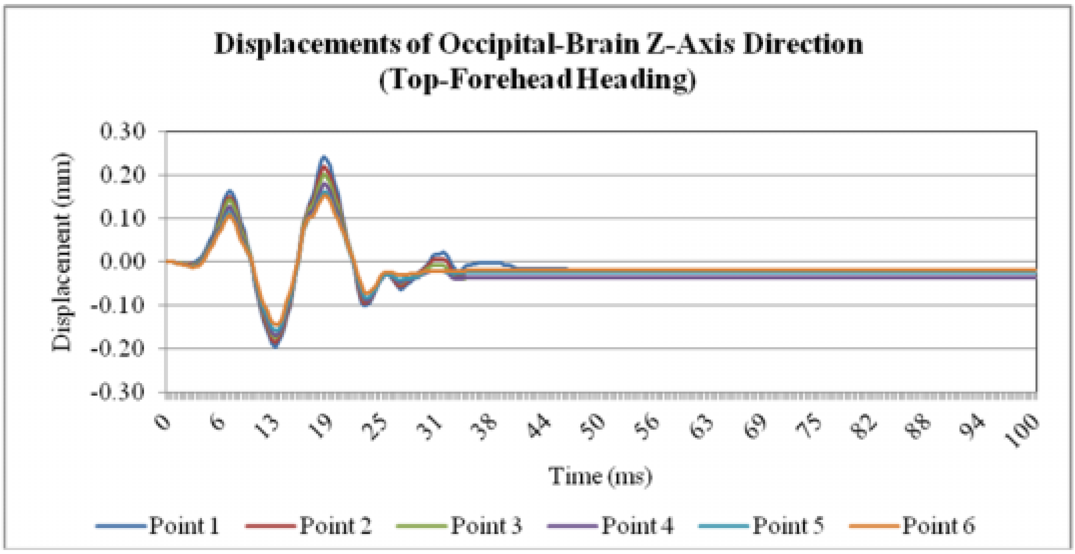


Figure 5.53: Displacements of occipital-brain z-axis direction on top-forehead heading

5.4.1 Result of Validation for Top-forehead heading

This section presents the validation for top-forehead heading. Here the comparison between the two speeds of sepak takraw ball was from FEA simulation and experiment. A graph of the speed of the center of the sepak takraw ball during top-forehead heading is as shown in Figure 5.54. The figure shows that the speed before impact is 13.583 m/s and the contact time is 0.01023 sec. After impact, it is 9.22 m/s. The difference between FEA simulation and experiment is 3.31%. The video recorded until 0.0639 sec of the experiment.

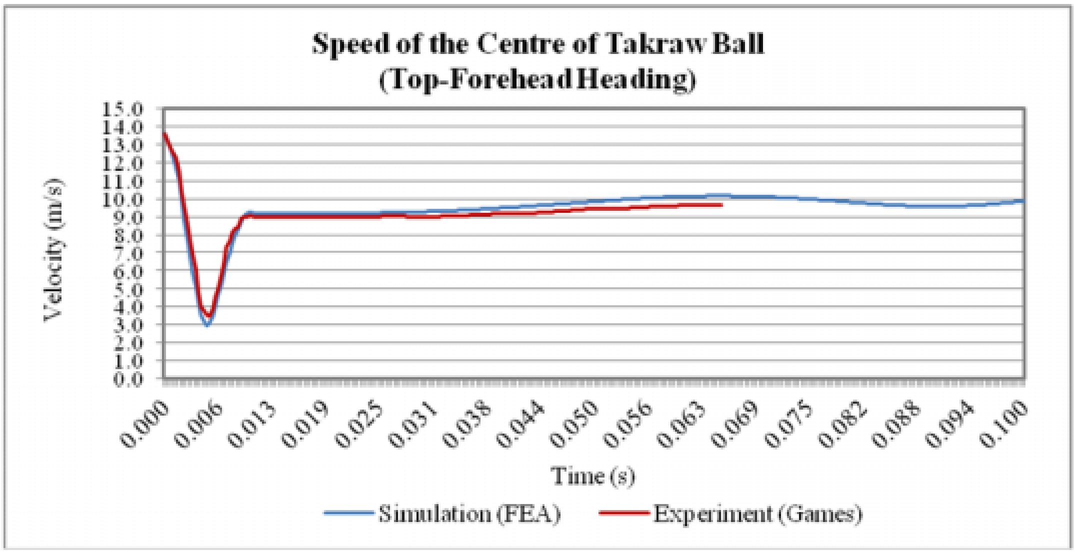
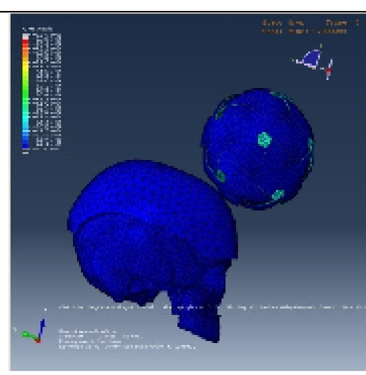
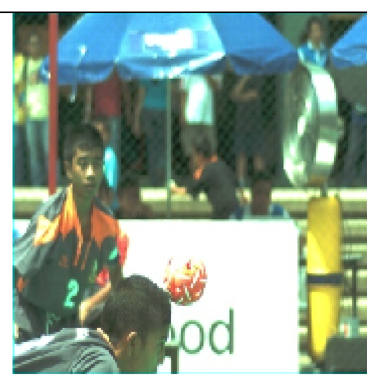
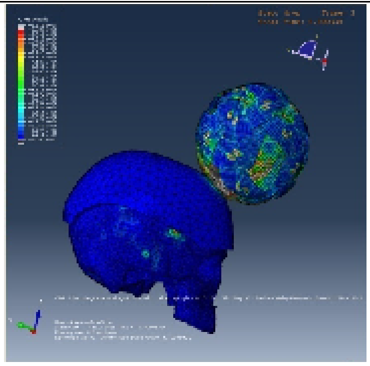
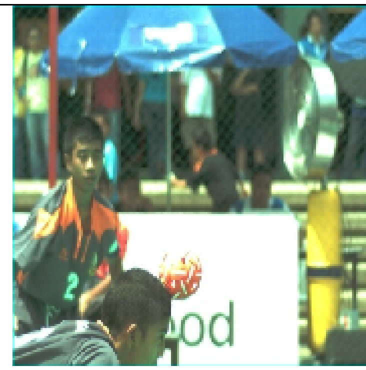
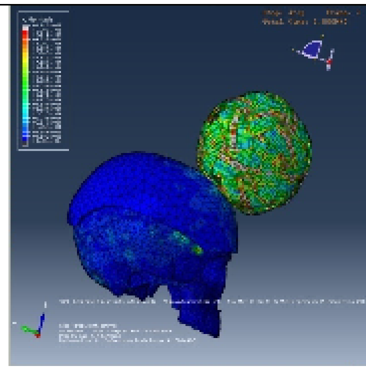
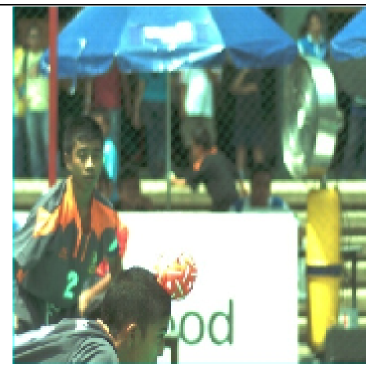
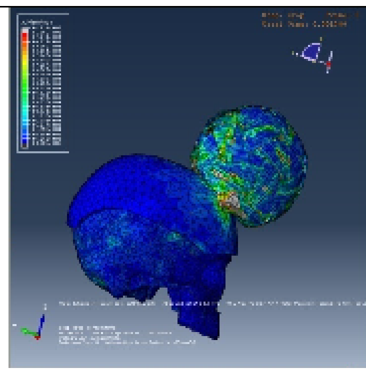
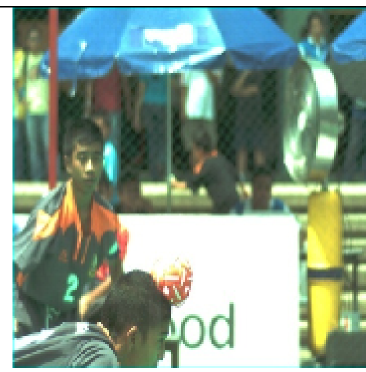
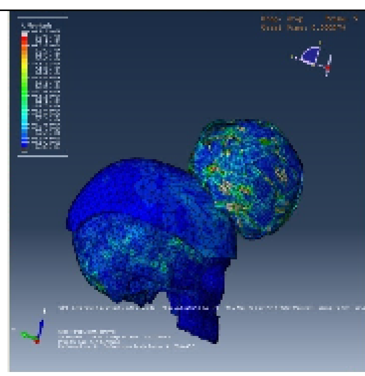
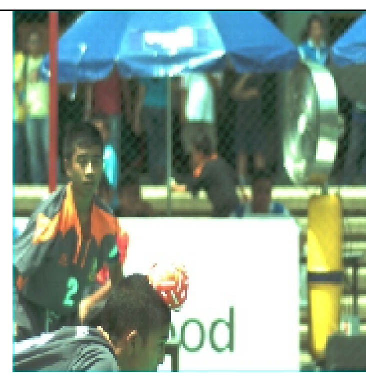


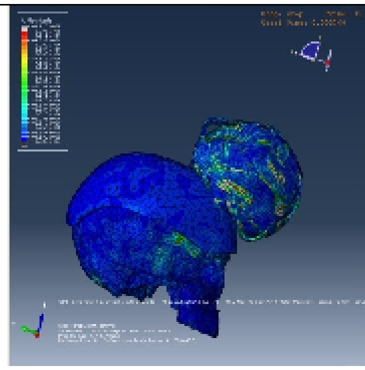
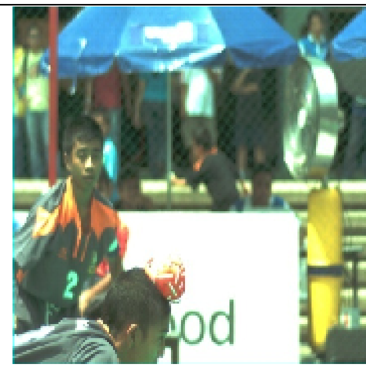
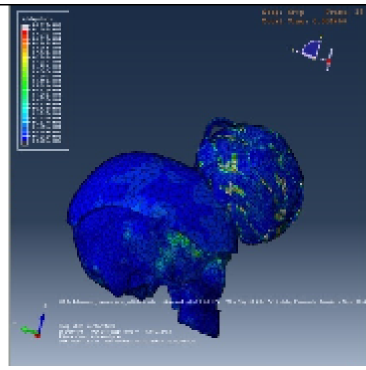
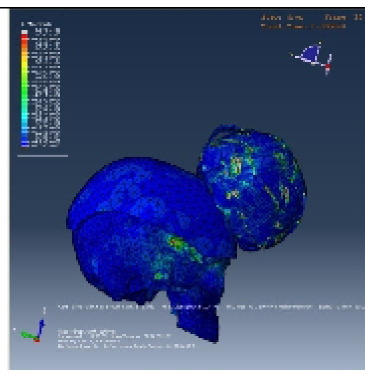
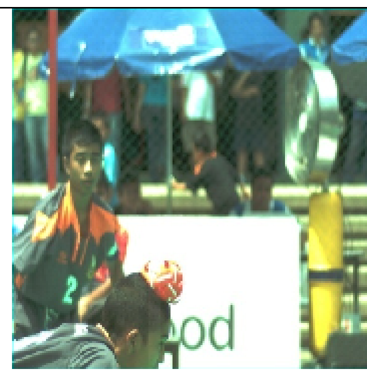
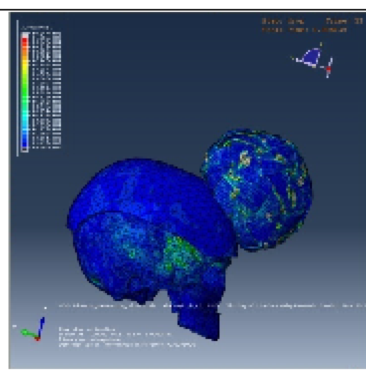
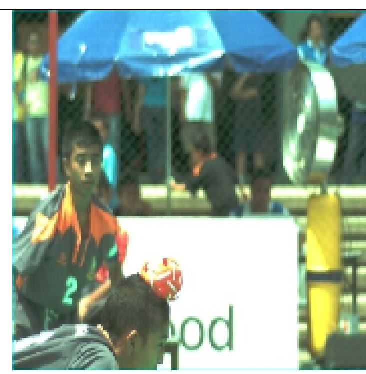
Figure 5.54: Speed of centre of sepak takraw ball on top-forehead heading

The next step is to compare the contact time of FE simulations and experiment for the top-forehead heading. These are shown in Table 5.3. The result shows difference of the contact times of 7.0 %.

Table 5.3: Comparison of FEA Simulation and High speed camera data for top-forehead heading

Time (ms)	FE Simulation	High Speed Camera
(0.0) Before heading		

1 first time of top-forehead heading		
2		
3		
4		

5		
6		
7		
8		

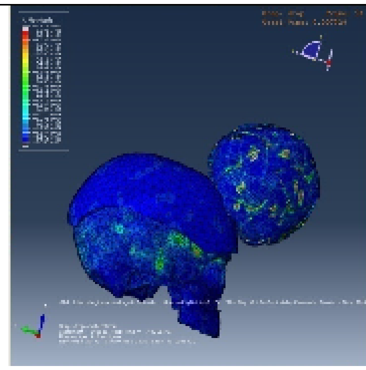
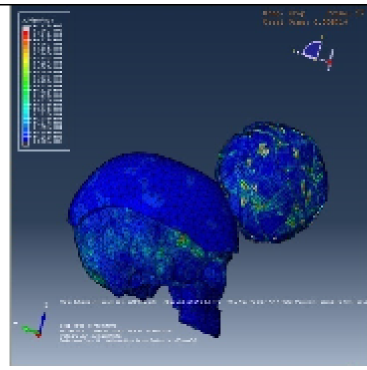
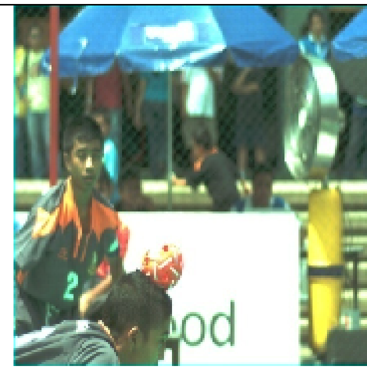
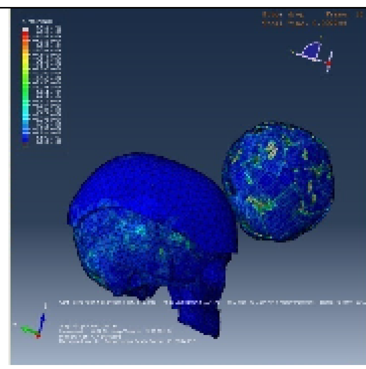
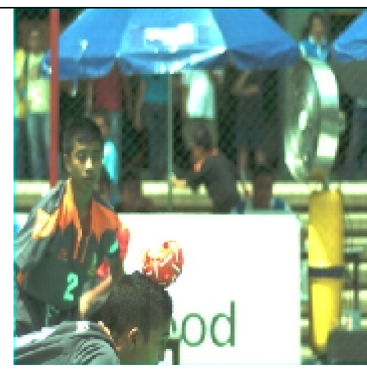
9		
10		
End of top-forehead heading		
	The time is 10.23 ms	The time is 11.00 ms

Table 5.3: Comparison of FEA Simulation and High speed camera data for top-forehead heading

5.4.2 Head Injury Criterion and Head Impact Power of Top-Forehead Heading

This section presents the results of HIC and HIP calculation for the top-forehead heading. These use data of displacement, velocity, acceleration, angular displacement, angular velocity and angular acceleration of centre of gravity of the brain.

Figure 5.55 is the graph of the displacement of the centre of gravity of the brain for top-forehead heading. The maximum displacement of the centre of gravity of the brain is 0.181 mm and the minimum is -0.057 mm, both of them in y-axis.

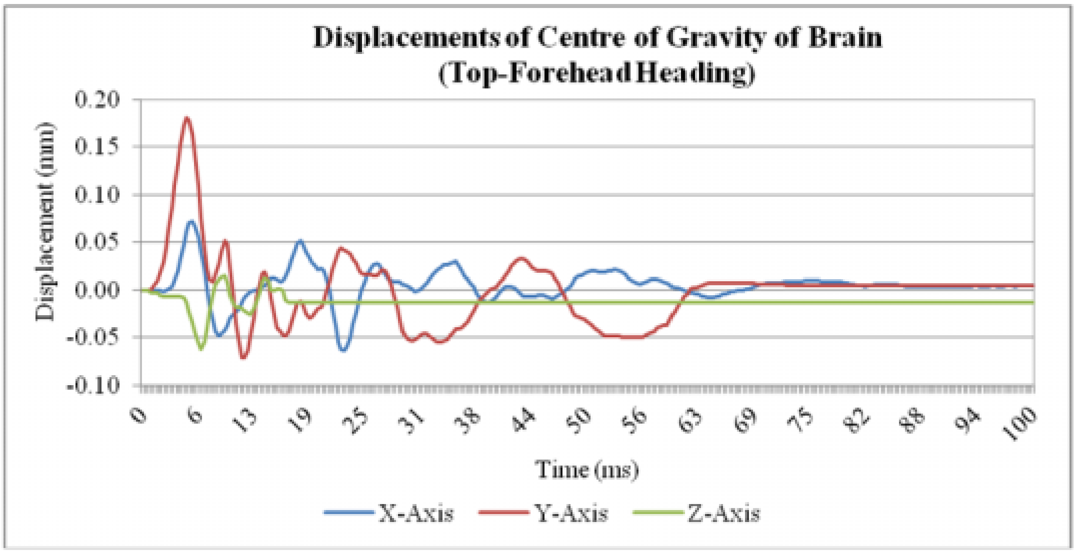


Figure 5.55: Displacement of centre of gravity of brain for top-forehead heading

Figure 5.56 is the velocity of the centre of gravity of the brain for top-forehead heading. It shows that the maximum velocity of the centre of gravity of the brain is 0.072 m/s and the minimum is -0.105 m/s in the y-axis.

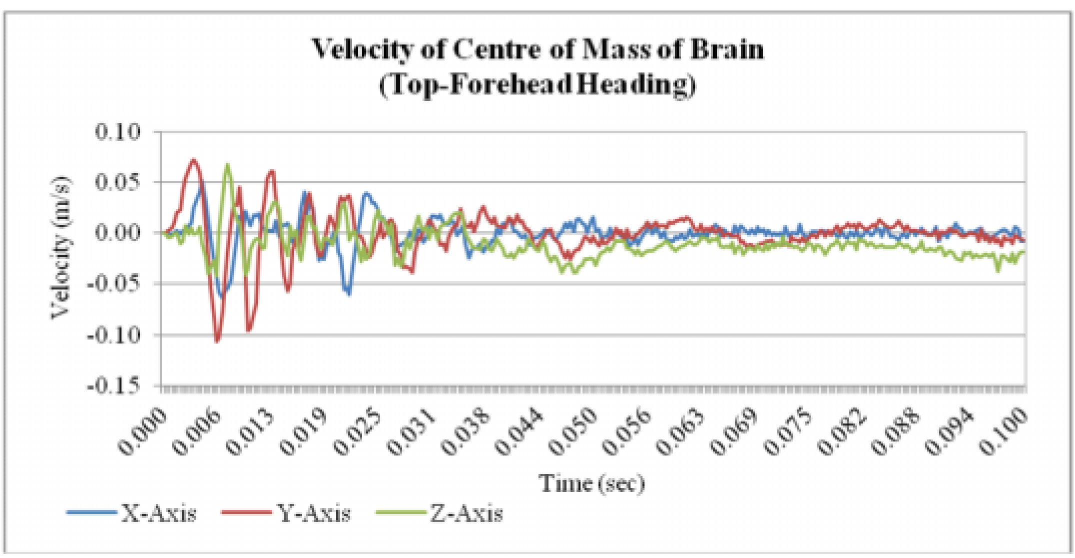


Figure 5.56: Velocity of centre of gravity of brain for top-forehead heading

Figure 5.57 displays the acceleration of the centre of gravity of the brain for top-forehead heading. It shows that the maximum magnitudes for positive and negative directions in x-axis are 1589.6 m/s^2 and -934.8 m/s^2. The maximum magnitudes for positive and negative directions in y-axis are 1501.5 m/s^2 and -1372.1 m/s^2. And finally in the z-axis are 1685.6 m/s^2 and -1187.4 m/s^2.

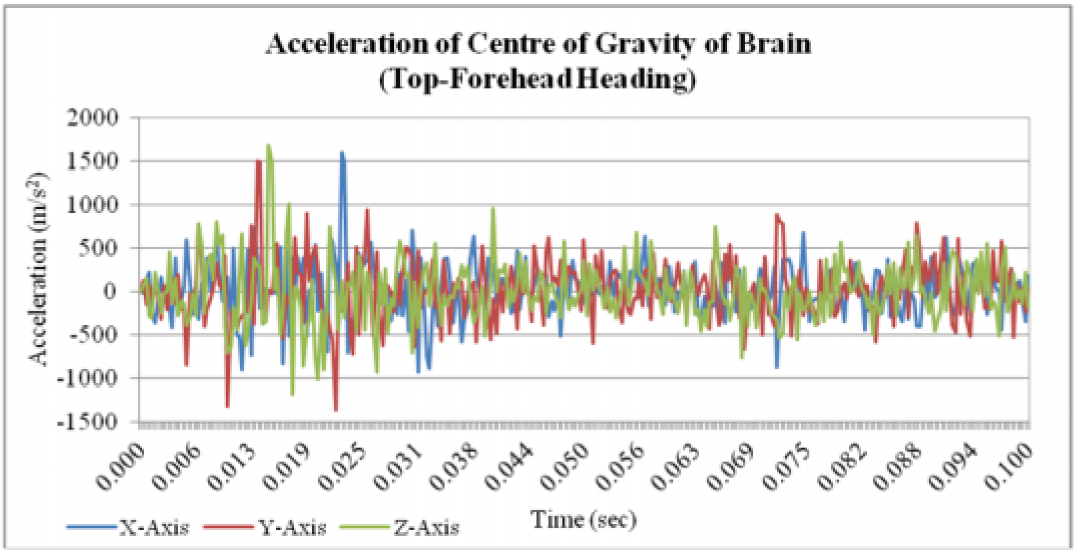


Figure 5.57: Acceleration of centre of gravity of brain for top-forehead heading

Figure 5.58 shows the angular displacements of the centre of gravity of the brain for top-forehead heading. It shows that the maximum angular displacement is 0.007 rad and the minimum is -0.006 rad, both of them in y-axis.

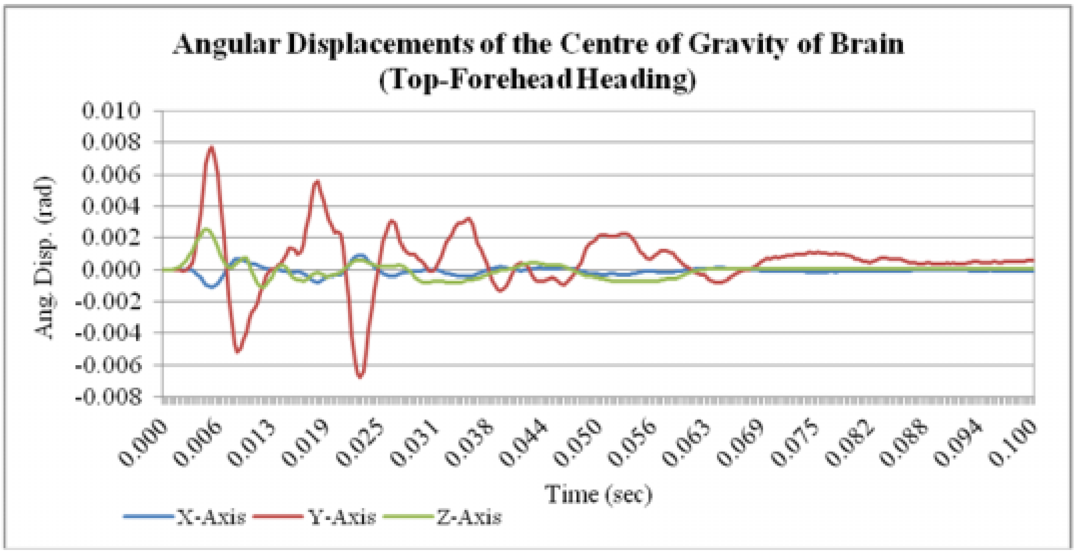


Figure 5.58: Angular displacements of centre of gravity of brain for top-forehead heading

The angular velocity of the centre of gravity of the brain for top-forehead heading is shown in Figure 5.9. It can be seen that the maximum angular velocity is 0.368 rad/s and the minimum is -0.320 rad/s, both of them in y-axis.

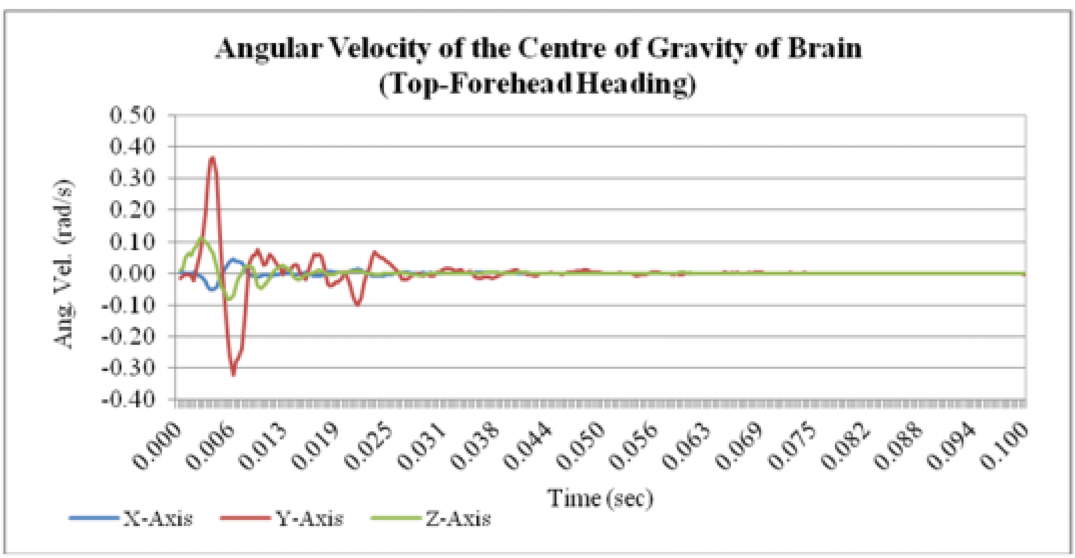


Figure 5.59: Angular velocity of the centre of gravity of brain for top-forehead heading

Figure 5.60 displays the angular accelerations of the centre of gravity of the brain for top-forehead heading. The maximum angular acceleration is 32.95 rad/s^2 and the minimum is -30.20 rad/s^2 in the y-axis.

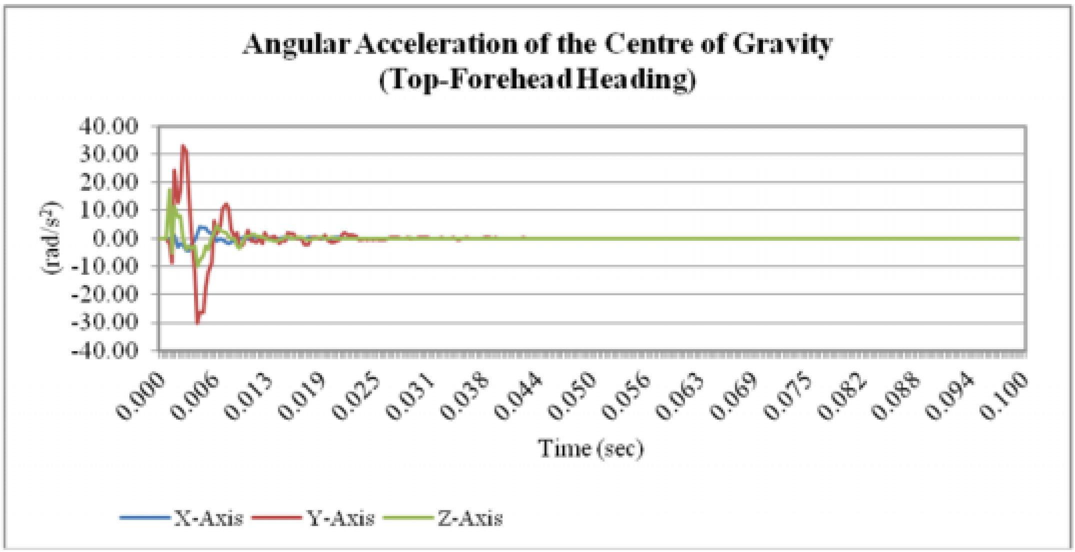


Figure 5.60: Angular accelerations of centre of gravity of brain for top-forehead heading

Based on the measurements above, the following HIC (refer to equation 2.2) and integration (refer to equation 2.4) for top-forehead is calculated using following information.

$f(a)_{resultant}$ = 1572.7 m/s^2	b = 0.00033 sec
$f(b)_{resultant}$ = 1522.7 m/s^2	a = 0 sec
t_1 = 0 sec	t_2 = 0.01023 sec

The HIC is 180.17 at the speed of sepak takraw ball of 13.58 m/s. Based on Newman et. al. (2000) as shown in Figure 5.61 the probability of concussion is 34 % (red line) for top-forehead heading.

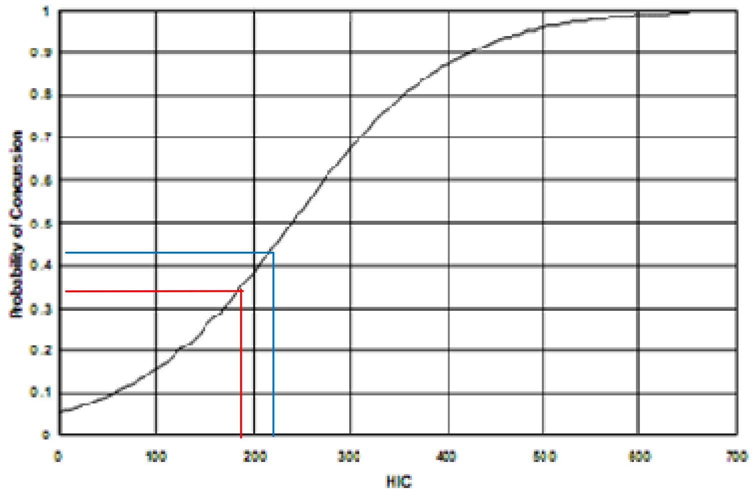


Figure 5.61: Probability of concussion based on HIC for top-forehead heading

Figure 5.62 shows the HIC for top-forehead heading at different speeds of the sepak takraw ball. The head injury criterion at different speeds of impact speed is shown in figure 5.61. The maximum HIC is 216.20 at 15 m/s indicating a 44% (blue line) probability of concussion.

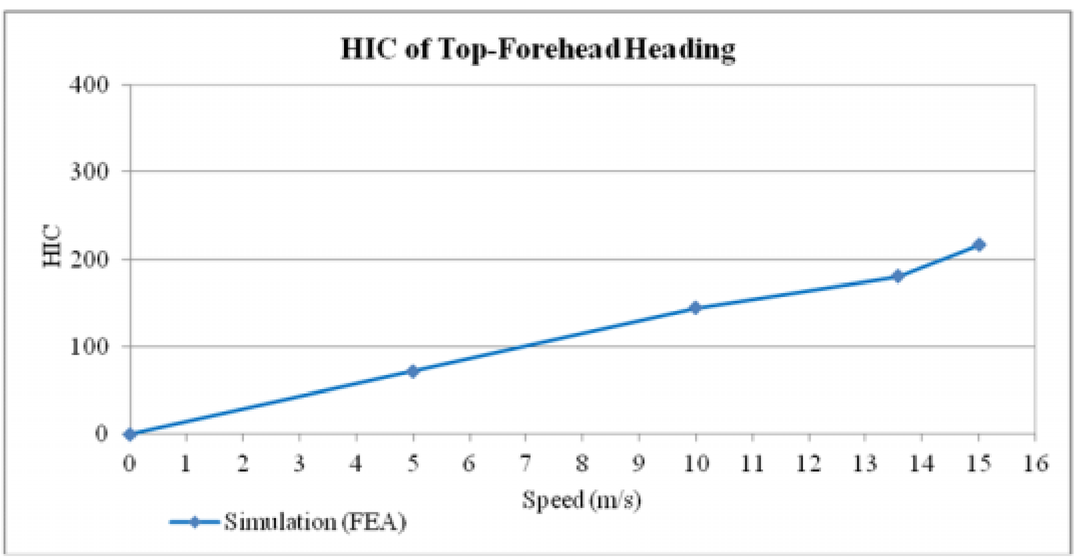


Figure 5.62: HIC of top-forehead heading with of variety of speed of sepak takraw ball

Subsequently, the following HIP (refer to equation 2.8) for top-forehead heading are calculated using following information.

$C_1 = 4.5$ kg	$C_2 = 4.5$ kg	$C_3 = 4.5$ kg
$C_4 = 0.016$ Nm/s^2	$C_5 = 0.024$ Nm/s^2	$C_6 = 0.022$ Nm/s^2
$a_{x1} = 1589.6$ m/s^2	$a_{y1} = 1551.5$ m/s^2	$a_{z1} = 1585.6$ m/s^2
$a_{x2} = 1490.5$ m/s^2	$a_{y2} = 1480.6$ m/s^2	$a_{z2} = 1489.8$ m/s^2
$t_1 = 0$ sec	$t_2 = 0.00033$ sec	
$\alpha_{x1} = 4.175$ rad/s^2	$\alpha_{y1} = 32.952$ rad/s^2	$\alpha_{z1} = 11.432$ rad/s^2
$\alpha_{x2} = 3.678$ rad/s^2	$\alpha_{y2} = 30.960$ rad/s^2	$\alpha_{z2} = 7.422$ rad/s^2

The HIP is 10.749 kW at a speed of 13.581 m/s. Based on Newman et. al. (2000) as shown in Figure 5.63, the HIP probability of concussion is 32 % (red line) for top-forehead heading.

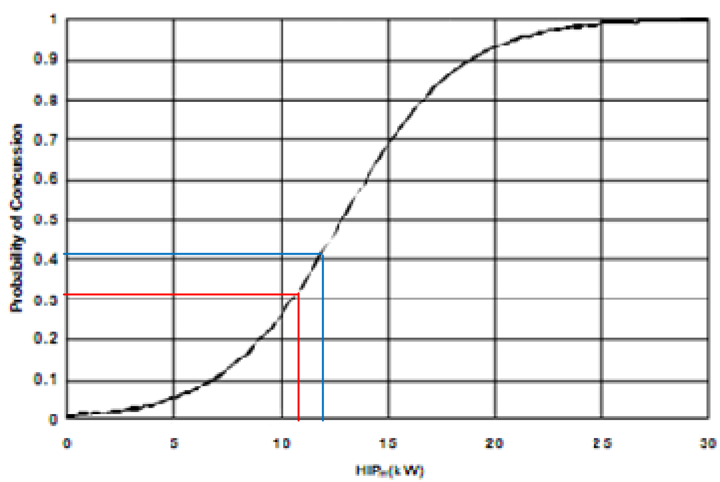


Figure 5.63: Probability of concussion based on HIP for top-forehead heading

The HIP of top-forehead heading at various speeds of the sepak takraw ball is shown in Figure 5.64. The maximum value is 12.33 kW at 15 m/s indicating a 42 % (blue line) of probability of concussion (see Figure 5.63).

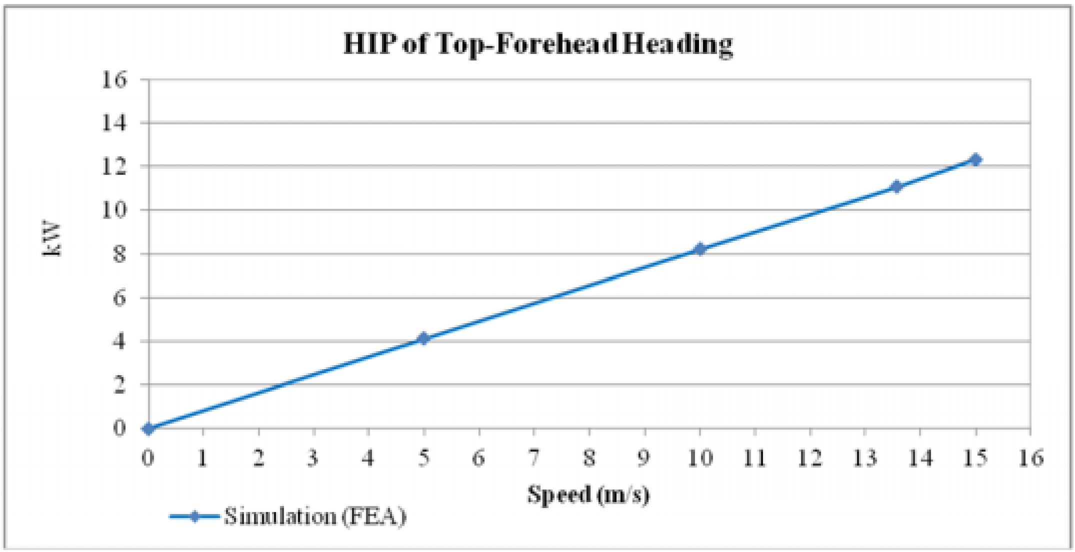


Figure 5.64: HIP of top-forehead heading with of variety of speed of sepak takraw ball

5.5 FEA Result of Side-Forehead Heading

This section presents the result of the total impact force of the head, displacement of skull, and displacement of whole brain, 6 points displacement in frontal-brain and 6 points displacement in the occipital-brain of side-forehead heading. Figure 5.65 displays the finite element simulation of the side-forehead heading.

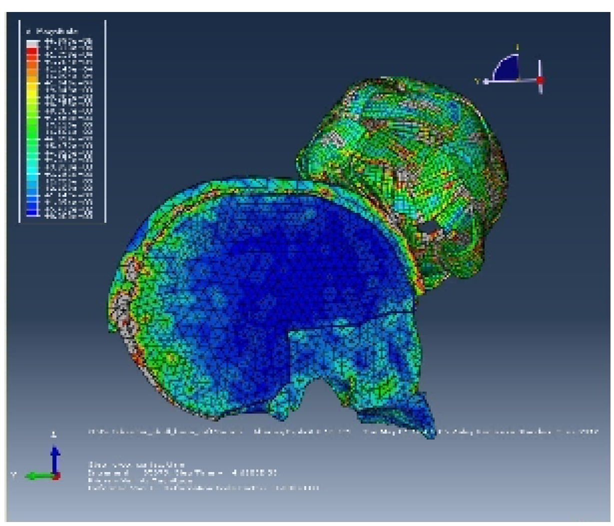


Figure 5.65: Finite element simulation of side-forehead heading

Figure 5.66 is the total impact force on the head during side-forehead heading. It shows that the maximum force on the head is 549.558 N and the contact time is 0.01056 sec with the speed of the ball before impact of 10.958 m/s.

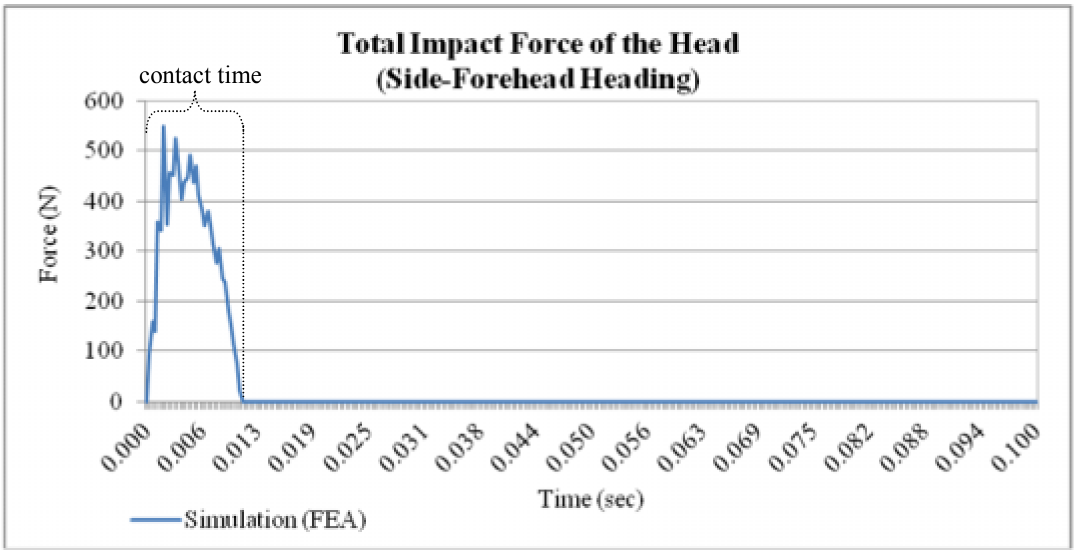


Figure 5.66: Total impact force of the head on side-forehead heading

Figure 5.67 presents the average displacements of the whole brain during side-forehead heading. It shows that the displacements of the skull on impact during side-forehead heading in the y-axis has a maximum value of 0.152 mm and a minimum value of -0.052 mm.

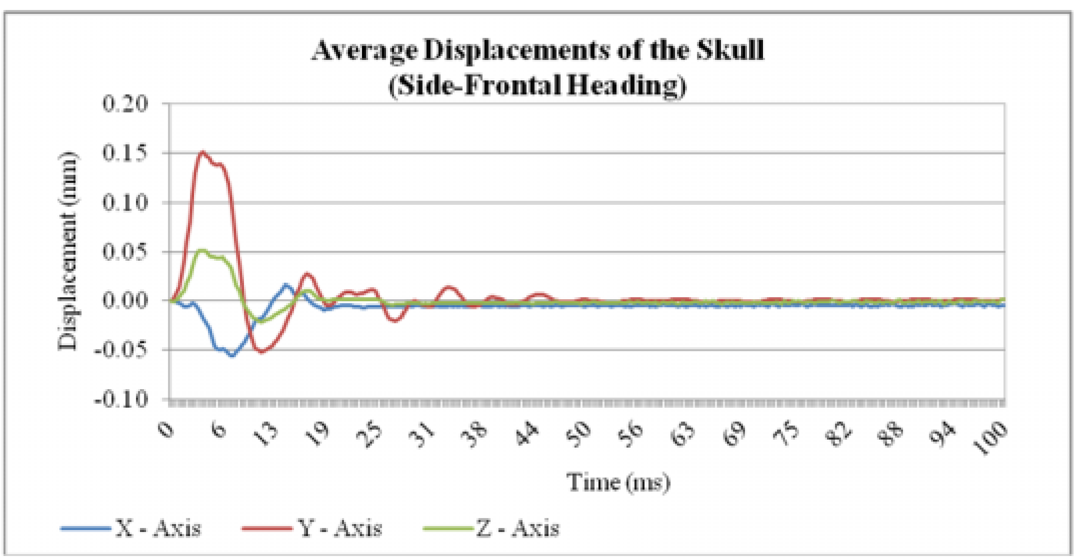


Figure 5.67: Average displacements of the skull on side-forehead heading

Figure 5.68 displays the average displacements of the whole brain during side-forehead heading. It shows that the displacement of the brain during side-forehead heading in the y-axis has a maximum value of 0.297 mm and a minimum value of -0.143 mm. After impact at 100 ms in simulation, the displacement in the x-axis is -0.003 mm, y-axis is -0.056 mm and z-axis is 0.005 mm.

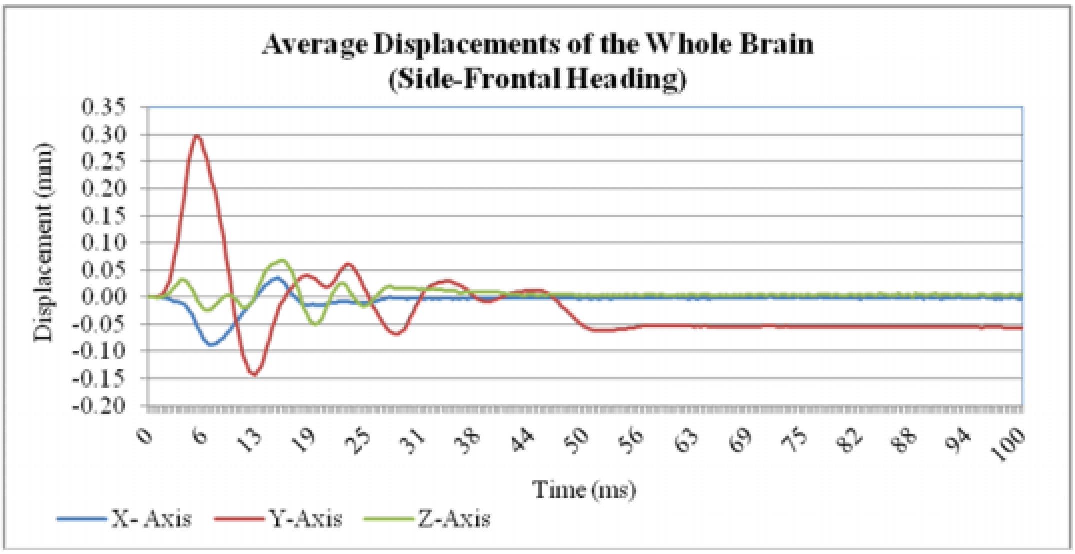


Figure 5.68: Average displacements of the whole brain on side-forehead heading

Figure 5.69 is the average acceleration of the whole brain during side-forehead heading. It shows that the average acceleration of the brain during side-forehead heading has a maximum magnitude for positive and negative directions in x-axis are 60.889 m/s^2 and -46.002 m/s^2. The maximum magnitudes for positive and negative directions in y-axis are 89.418 m/s^2 and -200.115 m/s^2. And finally in the z-axis are 89.990 m/s^2 and -99.976 m/s^2.

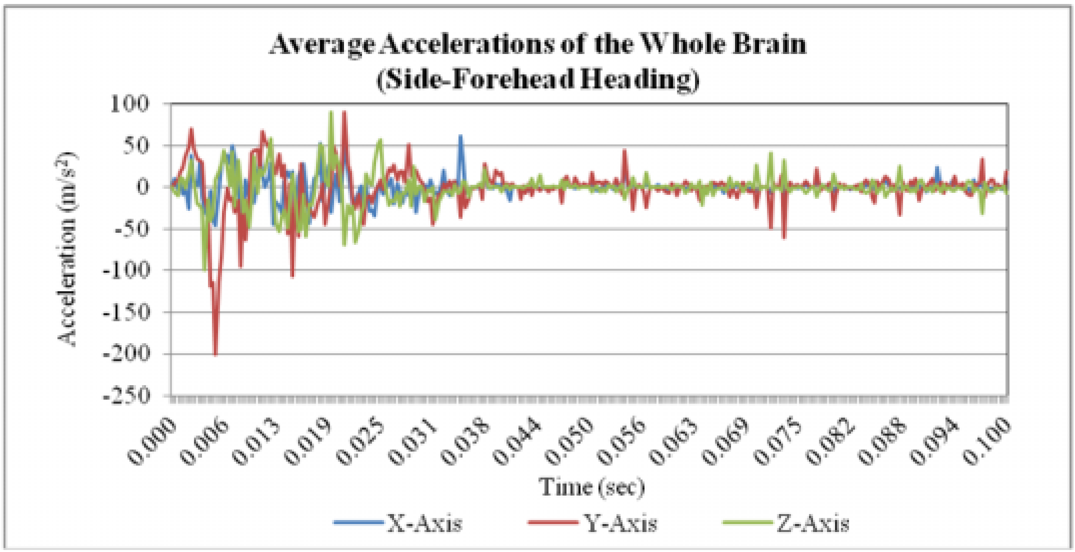


Figure 5.69: Average accelerations of the whole brain on side-forehead heading

Figure 5.70 presents the displacements of the frontal-brain in the x-axis direction during side-forehead heading. The maximum displacement of the frontal-brain in the x-axis direction during side-forehead heading is 0.028 mm and the minimum is -0.145 mm, both of them at point 1. The displacements of after impact at 100 ms in simulation for point 1 is -0.019 mm, point 2 is -0.031mm, point 3 is -0.017 mm, point 4 is -0.021 mm, point 5 is -0.030 mm and point 6 is -0.033 mm.

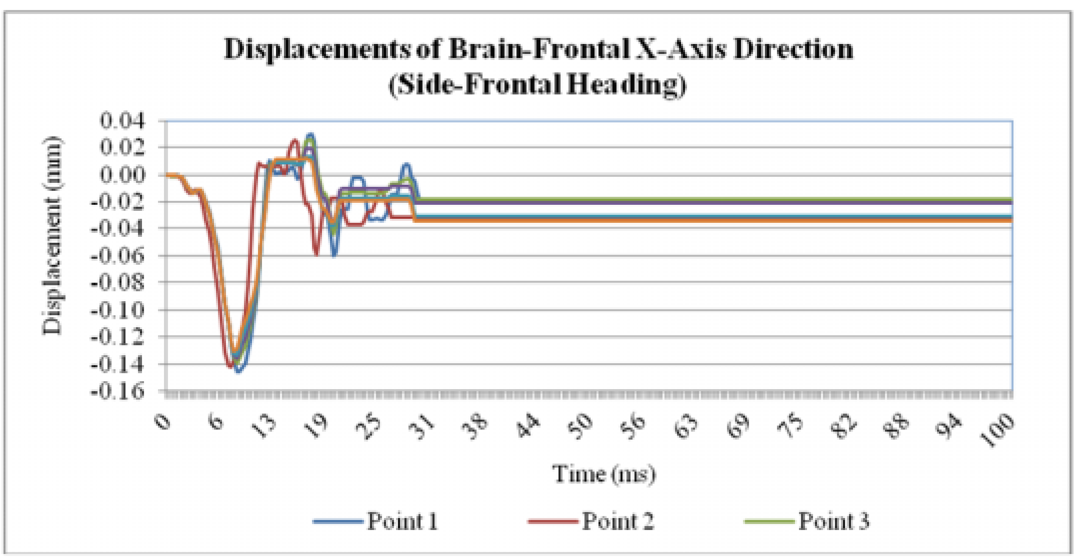


Figure 5.70: Displacements of frontal-brain x-axis direction on side-forehead heading

Figure 5.71 shows the displacements of the frontal-brain in the y-axis direction on side-forehead heading. The maximum displacement of frontal-brain y-axis direction on side-forehead heading during impact is 0.495 mm and the minimum is -0.279 mm, both of them at point 1. Then, the displacements after impact at 100 ms of simulation for point 1 is -0.181 mm, point 2 is -0.125 mm, point 3 is -0.127 mm, point 4 is -0.127 mm, point 5 is -0.119 mm and point 6 is -0.088 mm.

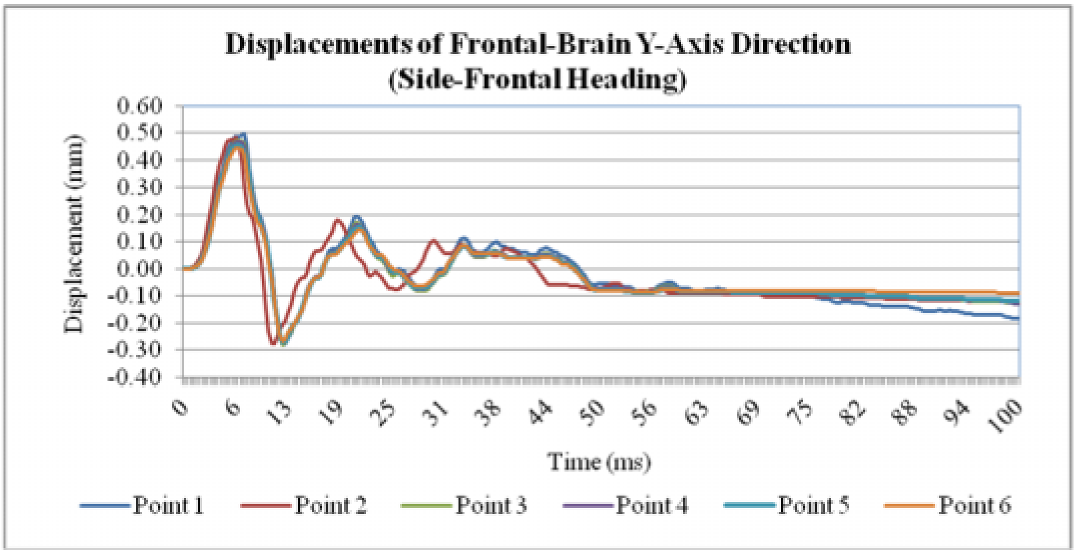


Figure 5.71: Displacements of the frontal-brain y-axis direction on side-forehead heading

Figure 5.72 shows the displacements of the frontal-brain in the z-axis direction on side-forehead heading. The maximum displacement of frontal-brain z-axis direction on side-forehead heading during impact is 0.322 mm and the minimum is -0.216 mm, both of them at point 1. Then, the displacement after impact at 100 ms of simulation for point 1 is -0.180 mm, point 2 is -0.060 mm, point 3 is -0.025 mm, point 4 is -0.031mm, point 5 is -0.043 mm and point 6 is -0.036 mm.

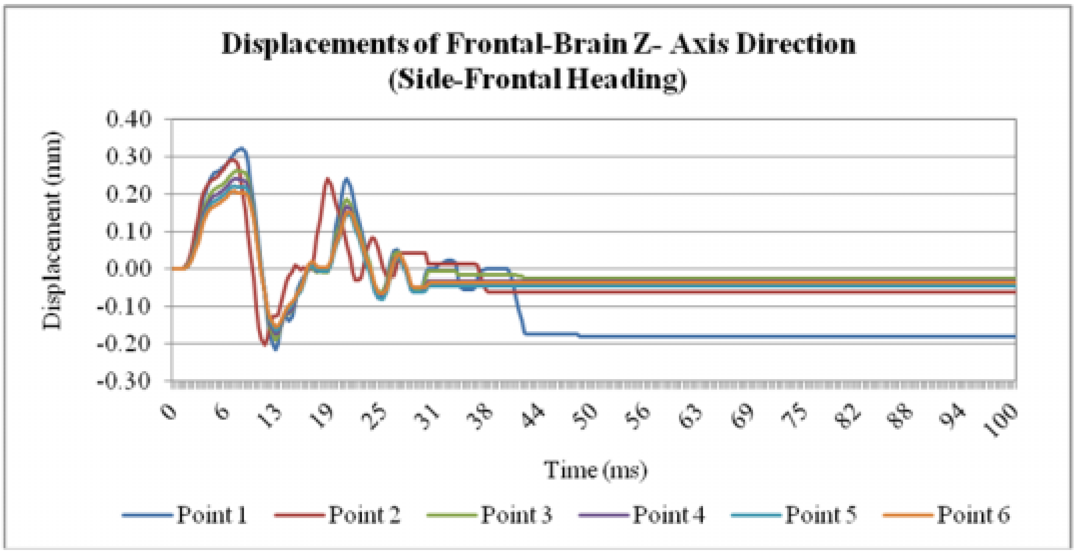


Figure 5.72: Displacements of frontal-brain z-axis direction on side-forehead heading

Figure 5.73 shows the displacements of the occipital-brain in the x-axis direction on side-forehead heading. The maximum displacements of occipital-brain x-axis direction on side-forehead heading during after impact is 0.082 mm at point 1 and the minimum -0.088 mm at point 6. Then, the displacements after impact at 100 ms of simulation for point 1 is 0.060 mm, point 2 is 0.060 mm, point 3 is 0.036 mm, point 4 is 0.007 mm, point 5 is 0.001 mm and point 6 is 0.002 mm.

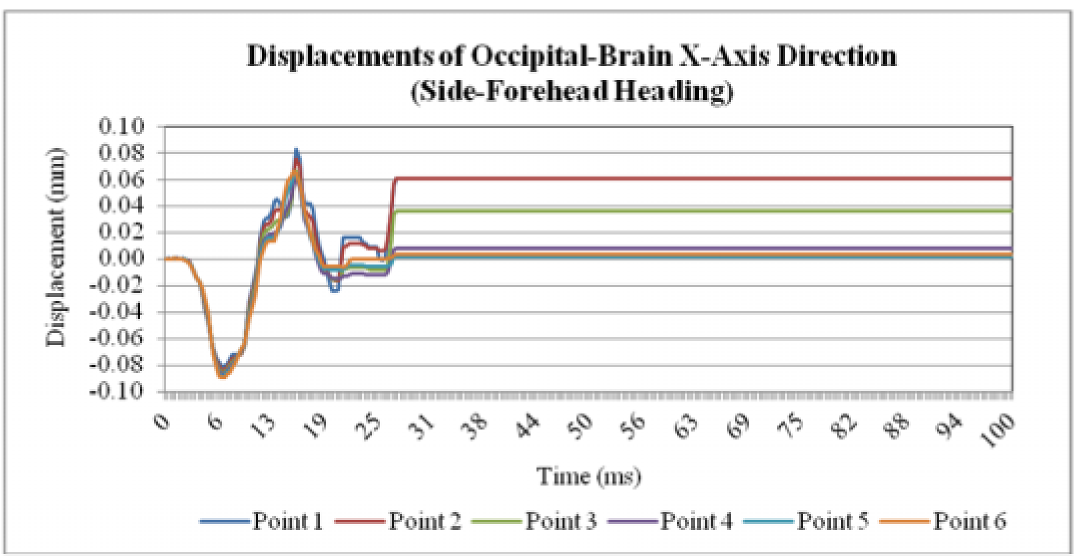


Figure 5.73: Displacements of occipital-brain x-axis direction on side-forehead heading

Figure 5.74 illustrates the displacements of the occipital-brain in the y-axis direction on side-forehead heading. The maximum displacement of occipital-brain y-axis direction on side-forehead heading during impact was 0.306 mm at point 6 and the minimum is -0.174 mm at point 4. Then, the displacements of after impacts at 100 ms of simulation for point 1 is -0.1162 mm, point 2 is -0.085 mm, point 3 is -0.083 mm, point 4 is -0.093 mm, point 5 is -0.087 mm and point 6 is -0.066 mm.

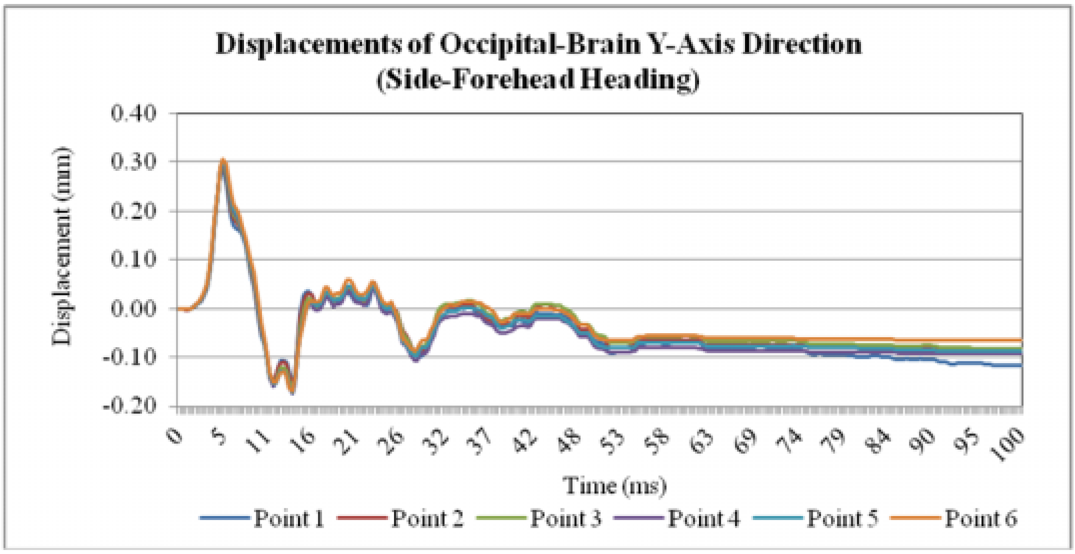


Figure 5.74: Displacements of occipital-brain y-axis direction on side-forehead heading

Figure 5.75 shows the displacements of the occipital-brain in the z-axis direction on side-forehead heading. The maximum displacement of occipital-brain z-axis direction on side-forehead heading during impact is 0.537 mm and the minimum is -0.382 mm, both of them at point 1. Then, the displacements after impact at 100 ms of simulation for point 1 is -0.263 mm, point 2 is -0.193 mm, point 3 is -0.070 mm, point 4 is 0.026 mm, point 5 is 0.035 mm and point 6 is 0.057 mm.

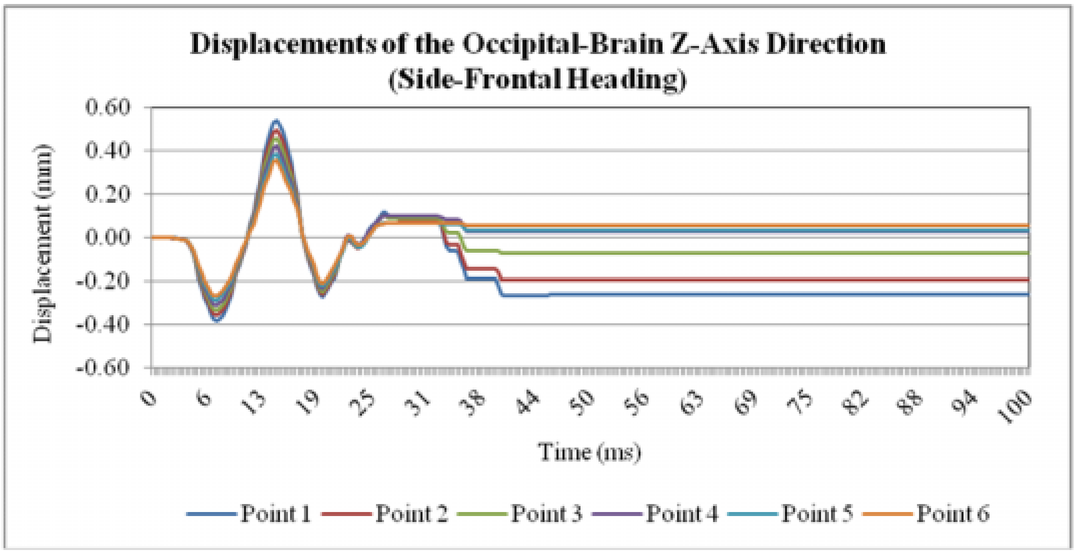


Figure 5.75: Displacements of the occipital-brain z-axis direction on side-forehead heading

5.5.1 Validation for Side-forehead heading

Validation for side-forehead heading is performed by comparing the speed of the sepak takraw ball from FEA simulation with experimental results Figure 5.76 is a graph of the speed of the centre of the sepak takraw ball during heading with the top-forehead. It shows the difference of 5.17% between FE simulation and experiment.

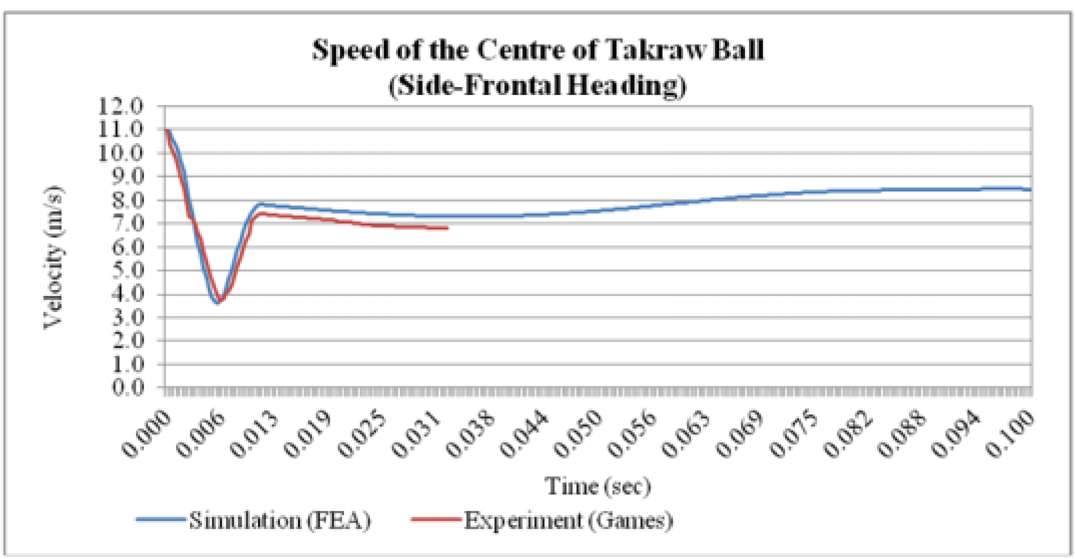
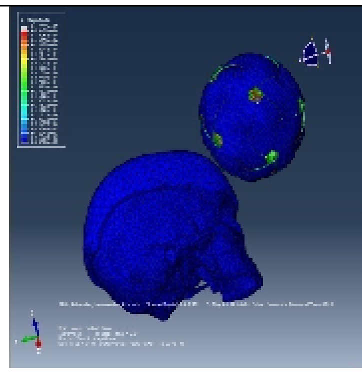
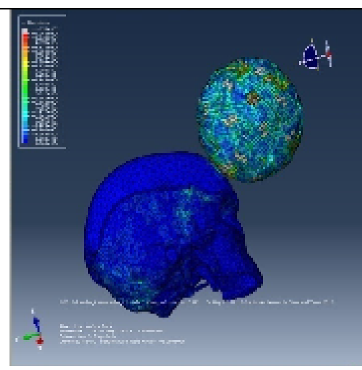
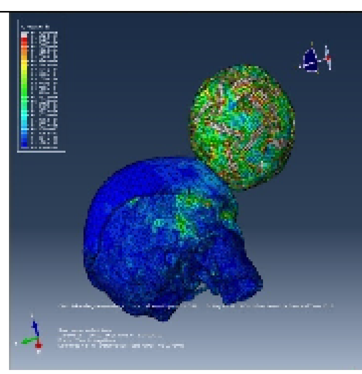
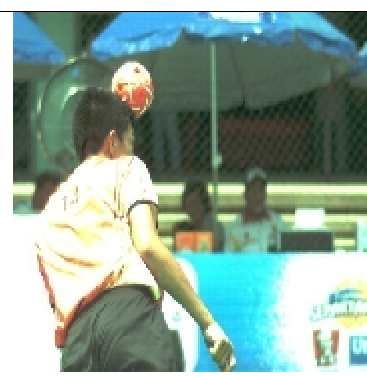
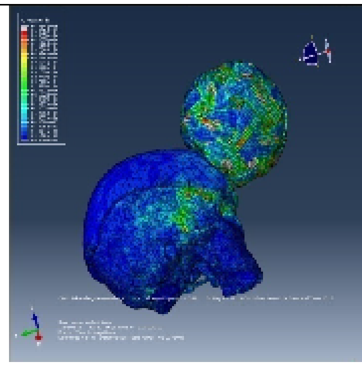
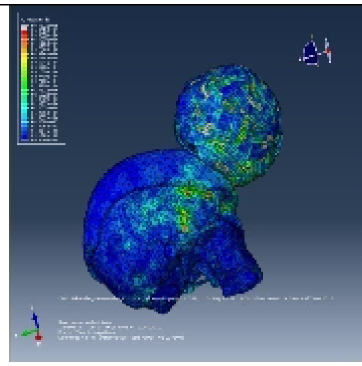
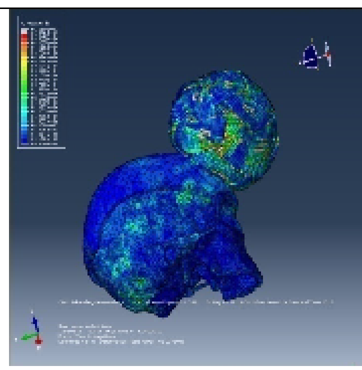
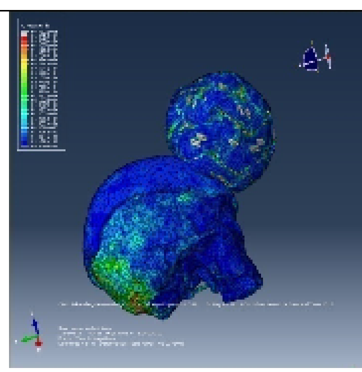
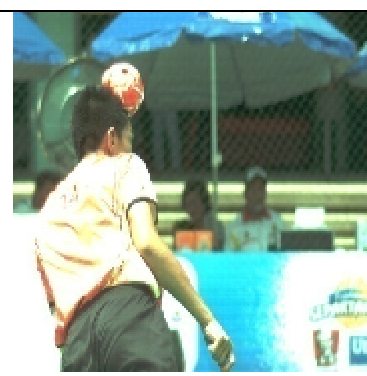


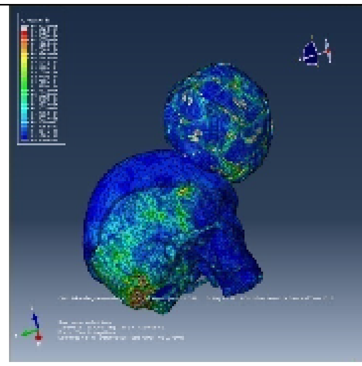
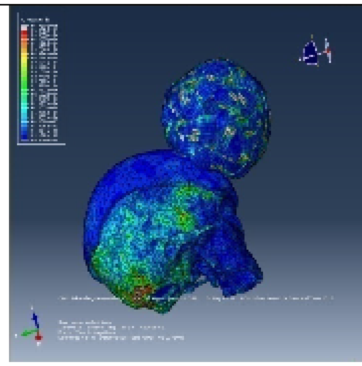
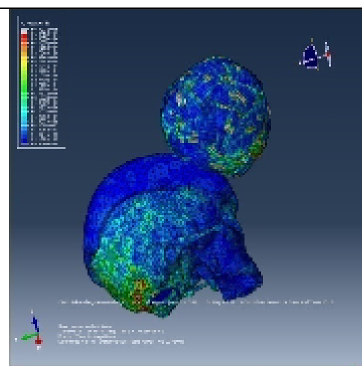
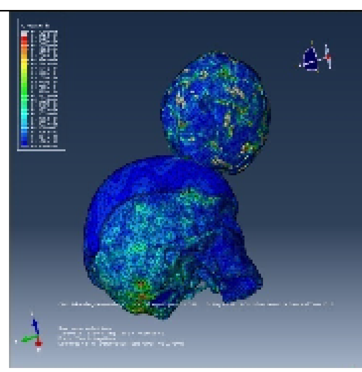
Figure 5.76: Comparison of speed of the centre of sepak takraw ball for side-forehead heading

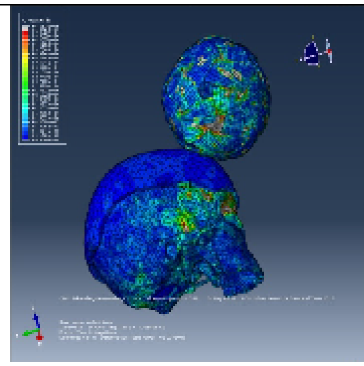
The next step is to compare the contact time between FE simulations and the recordings from high speed video camera for the side-forehead heading. Table 5.4 presents a comparison of the video images and FEA simulation. It shows that the difference of the contact time is 1.0 %.

Table 5.4: Comparison of contact time between FE simulation and high speed camera pictures for side-forehead heading

Time (ms)	FE Simulation	High Speed Camera
(0.0) Before heading		
1 first time of side-forehead heading		
2		

3		
4		
5		
6		

7		
8		
9		
10		

End of side–forehead heading		
	The time is 10.56 ms	The time is 11.00 ms

5.5.2 Head Injury Criterion and Head Impact Power of Side-Forehead Heading

This section presents the calculation of the head injury criterion (HIC) and head impact power (HIP) for the side-forehead heading. The displacement of the centre of gravity of the brain during side-forehead heading is illustrated in Figure 5.77. It shows that the maximum of displacement is 0.315 mm and the minimum value is -0.200 mm in the y-axis.

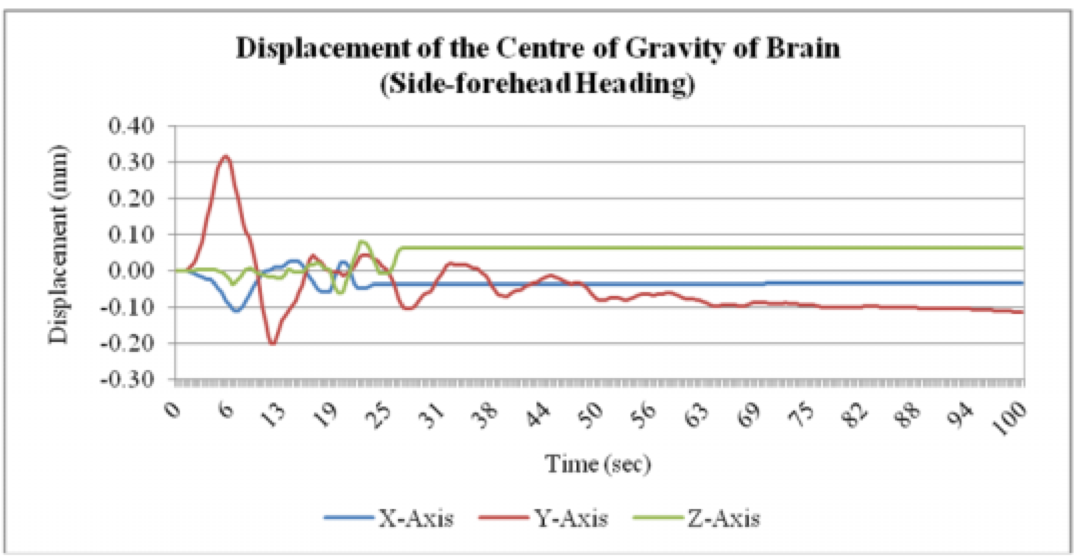


Figure 5.77: Displacement of centre of gravity of brain for side-forehead heading

Figure 5.78 shows the velocity of the centre of gravity of the brain during side-forehead heading. The maximum of velocity is 0.118 m/s and the minimum is -0.147 m/s in the y-axis.

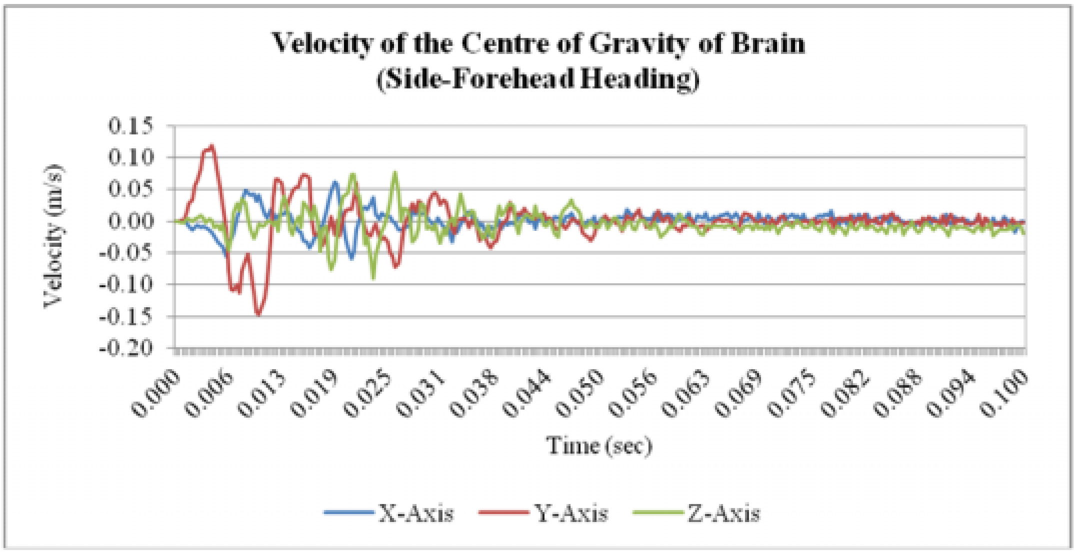


Figure 5.78: Velocity of the centre of gravity of brain for side-forehead heading

Figure 5.79 presents the accelerations of the centre of gravity of the brain during side-forehead heading. It shows that the maximum magnitudes for positive and negative directions in x-axis are 1586.7 m/s^2 and -1092.8 m/s^2. The maximum magnitudes for positive and negative directions in y-axis are 1591.3 m/s^2 and -1425.4 m/s^2. And finally in the z-axis are 1595.0 m/s^2 and -1280.2 m/s^2.

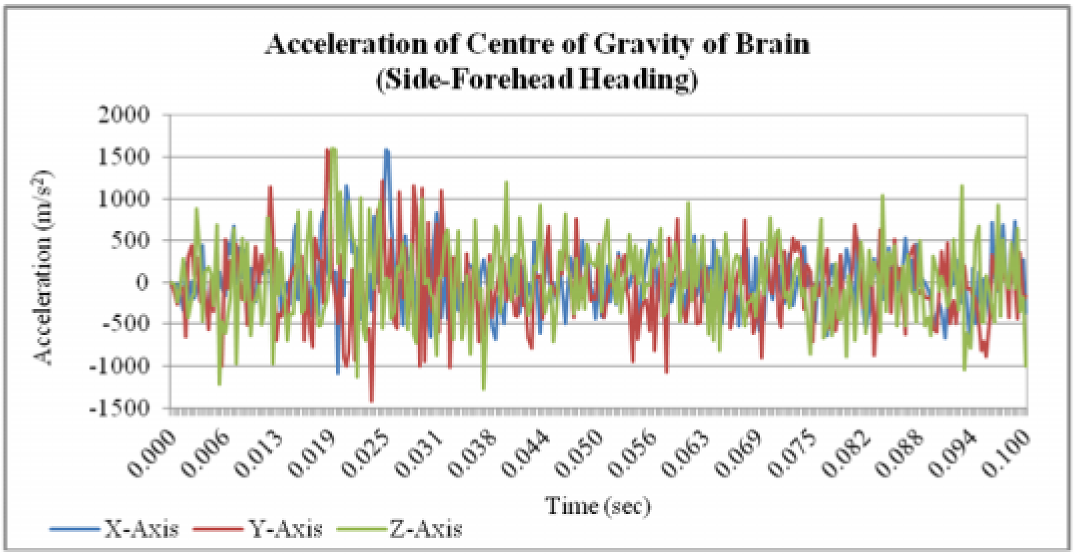


Figure 5.79: Accelerations of the centre of gravity of brain for side-forehead heading

Figure 5.80 presents the angular displacements of the centre of gravity of the brain during side-forehead heading. It shows that the maximum of angular displacement is 0.004 radian in the z-axis and the minimum is -0.011 radian in the y-axis.

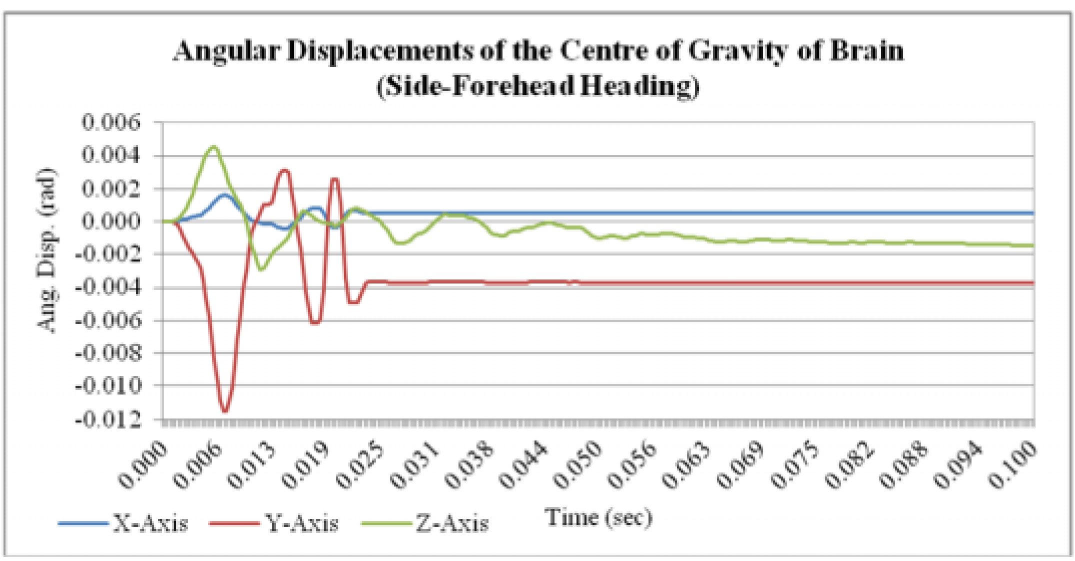


Figure 5.80: Angular Displacements of centre of gravity of brain for side-forehead heading

Figure 5.81 displays the angular velocity of the centre of gravity of the brain during side-forehead heading. The maximum angular velocity is 0.196 rad/s and the minimum is -0.244 rad/s, both of them in y-axis.

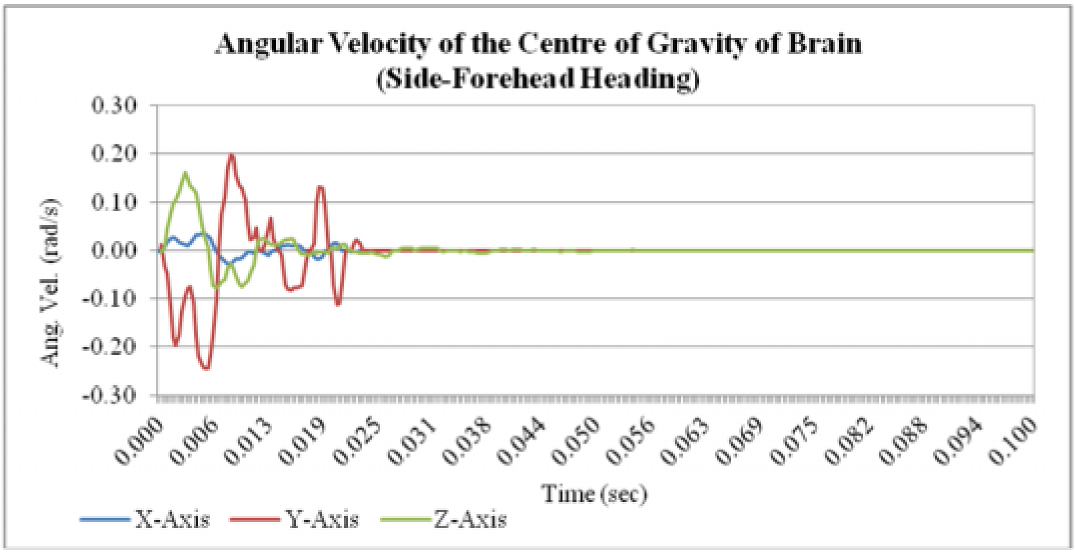


Figure 5.81: Angular velocity of the centre of gravity of brain for side-forehead heading

The angular accelerations of centre of gravity of the brain during side-forehead heading are shown in Figure 5.82. It shows that the maximum angular acceleration is 20.29 rad/s^2 and minimum is -17.72 rad/s^2, both of them in y-axis.

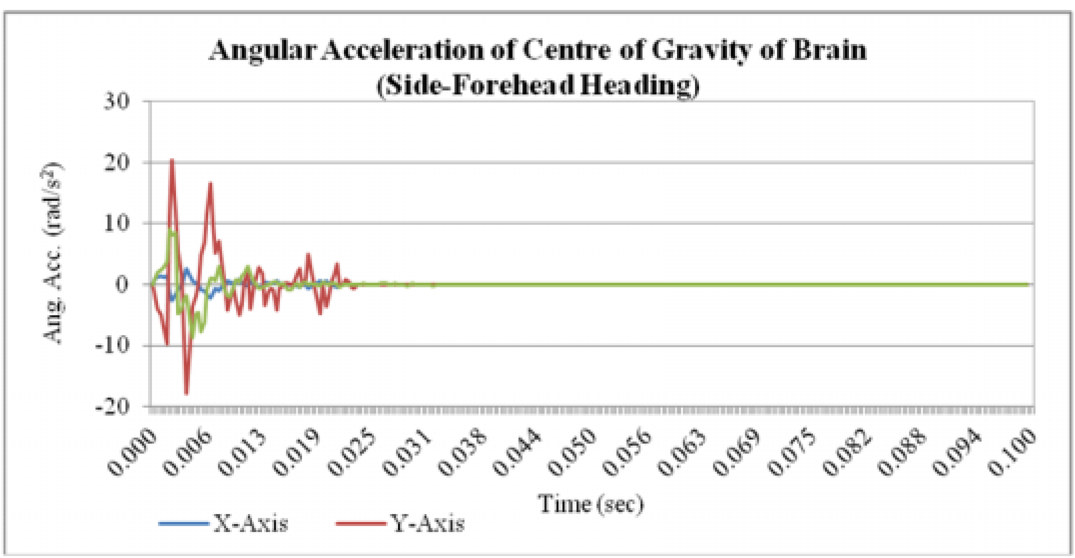


Figure 5.82: Angular accelerations of centre of gravity of brain for side-forehead heading

Based on the measurements above, the following HIC (refer to equation 2.2) for side-forehead is calculated using following information.

$f(a)_{resultant}$ = 1631.019 m/s^2 a = 0 sec

$f(b)_{resultant}$ = 1593.821 m/s^2 b = 0.00033 sec

t_1= 0 sec t_2= 0.01056 sec

The HIC is calculated as 190.320. Based on Newman et. al. (2000) as shown in Figure 5.83 the HIC probability of concussion is 36% (red line) for side-forehead heading at a speed of 10.958 m/s.

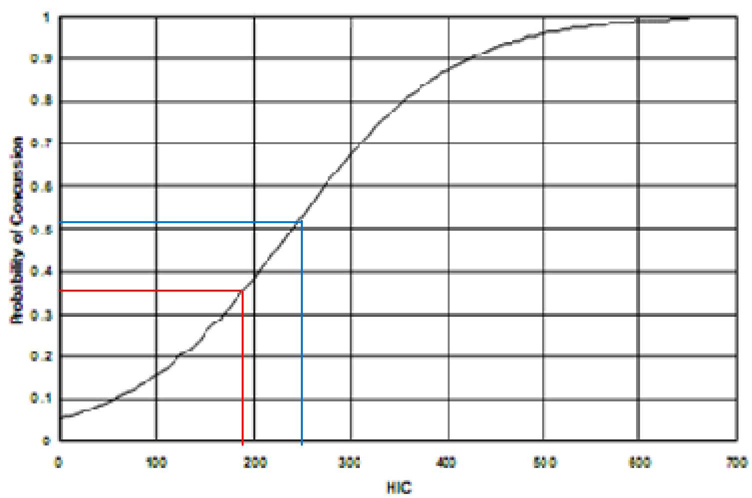


Figure 5.83: Probability of concussion based on HIC for side-forehead heading

The head injury criterion of side-forehead heading at different speeds of the sepak takraw ball is shown in Figure 5.84. The maximum value is 250.876 at 15 m/s giving a 52 % (blue line) probability of concussion (see Figure 5.83).

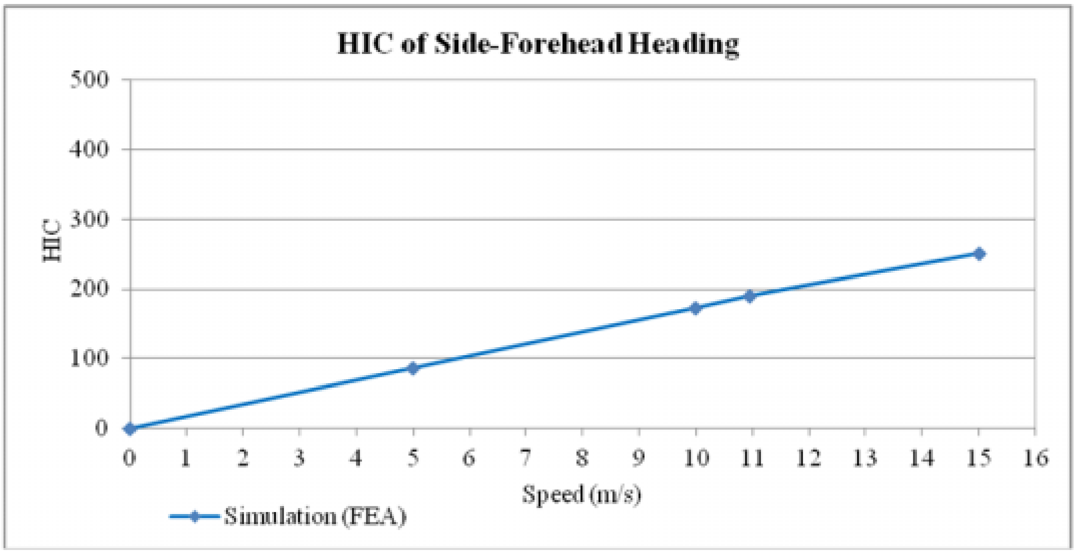


Figure 5.84: HIC of side-forehead heading with of variety of speed of sepak takraw ball

Subsequently, the following HIP (refer to equation 2.8) for side forehead heading are calculated using following information.

C_1 = 4.5 kg $\quad$ C_2 = 4.5 kg $\quad$ C_3 = 4.5 kg

C_4 = 0.016 Nm/s^2 $\quad$ C_5 = 0.024 Nm/s^2 $\quad$ C_6 = 0.022 Nm/s^2

a_{x1} = 1586.7 m/s^2 $\quad$ a_{y1} = 1591.3 m/s^2 $\quad$ a_{z1} = 1595.70m/s^2

a_{x2} = 1556.7 m/s^2 $\quad$ a_{y2} = 1548.3 m/s^2 $\quad$ a_{z2} = 1580.7 m/s^2

t_1 = 0 sec $\quad$ t_2 = 0.00033 sec

α_{x1} = 2.469 rad/s^2 $\quad$ α_{y1} = 20.292 rad/s^2 $\quad$ α_{z1} = 8.989 rad/s^2

α_{x2} = 1.403 rad/s^2 $\quad$ α_{y2} = 11.819 rad/s^2 $\quad$ α_{z2} = 8.002 rad/s^2

The the HIP is found to be 11.173 kW. Based on Newman et. al. (2000) as shown in Figure 5.85, the HIP probability of concussion is 34% (red line) for side-forehead heading at a speed of 10.958 m/s.

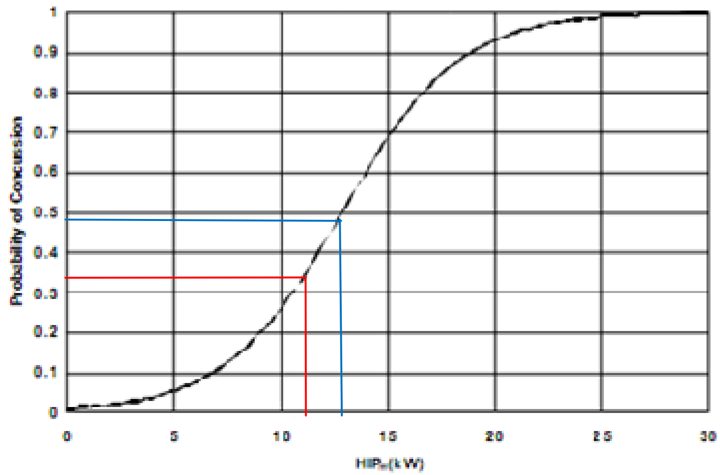


Figure 5.85: Probability of concussion based on HIP for front-forehead heading

The head impact power at different speeds are shown in Figure 5.86. The maximum value is 12.802 kW at 15 m/s of speed with a 49 % (blue line) probability of concussion (see Figure 5.85).

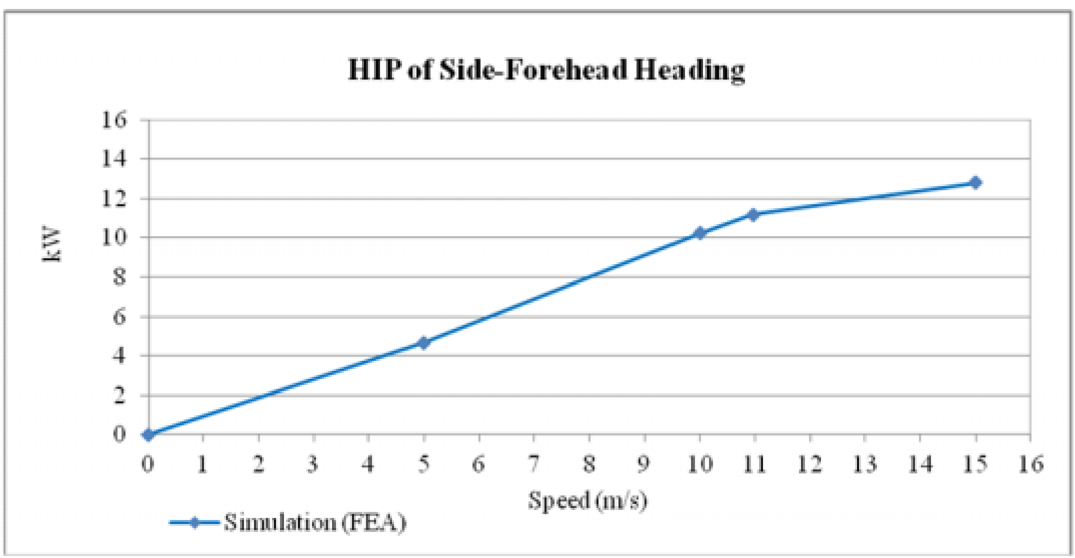


Figure 5.86: HIP of side-forehead heading with of variety of speed of sepak takraw ball

5.6 Discussions and Summary

Based on Lipton (2011), who conducted a research on the degeneration of brain cells at the frontal and occipital positions on soccer players, therefore, this study has illustrated the difference between displacements of brain at the frontal and occipital brain positions on sepak takraw players. Table 5.5 shows the difference between displacements at the frontal and occipital brain positions from a number of heading positions. For the x axis, all positions did not exceed 3-48% difference between frontal and occipital brain for every heading position except for side heading. Whilst for the y-axis at 52 - 67 % difference shows that brain will possibly be more damaged at the frontal position. Nonetheless, the side heading position provides an interesting proposition where the x-axis and z axis had higher displacements at the occipital brain compared to the frontal position. This is because side heading is more towards the back of the head position that may cause degeneration of brain to occur at the occipital from repetitive headings. Based on the interviews (see Table 4.31), the sepak takraw players could conduct headings up to 100 a day, and the killer players could conduct up to an average of 50 a day. Following Lipton (2011), a soccer player who conducts 1500 headings per year may develop degeneration of brain cells. Now, if we look at the soccer players of this study and take just 3 days of trainings in a week with about 150 headings/week and 7200 headings/year, therefore, their chance of developing degeneration of brain cells is even higher that the soccer players.

Table 5.5: Comparison of displacements between frontal-brain and occipital-brain base on type of heading

Type of headings	Axis	Max. disp. of frontal brain (mm)		Max. disp. of occipital brain (mm)		Comparison difference of disp. between frontal and occipital (%)	
		Pos. direction	Neg. direction	Pos. direction	Neg. direction	Pos.	Neg.
Drop test	X	0.046	-0.031	0.022	-0.015	47.8	48.4
	Y	0.025	-0.074	0.013	-0.047	52.0	63.5
	Z	0.029	-0.057	0.044	-0.018	65.9	31.6
Front-Forehead	X	0.058	-0.053	0.052	-0.055	10.3	3.6
	Y	0.715	-0.387	0.443	-0.255	62.0	65.9
	Z	0.462	-0.276	0.777	-0.519	59.5	53.2
Top-Forehead	X	0.426	-0.463	0.031	-0.044	7.3	9.5
	Y	0.203	-0.149	0.110	-0.100	54.2	67.1
	Z	0.153	-0.110	0.242	-0.196	63.2	56.1
Side-Forehead	X	0.028	-0.145	0.082	-0.088	65.9	60.7
	Y	0.495	-0.279	0.306	-0.174	61.8	62.4
	Z	0.322	-0.025	0.537	-0.382	40.0	56.5

Furthermore, Table 5.5 presents result of frontal brain displacement of this study that is similar to Chen et. al. (2012), except for the contact time. This difference can be attributed to different materials of impact on the skull. Figure 5.28 presented earlier shows similar pattern with the findings by Chen et. al. (2012) (see. Figure 2.7 in CHAPTER 2, section 2.3.3.4). This indicated that the FE model employed in this study is acceptable.

Following the graph by WSTC and Gadd (see Figure 2.3 in CHAPTER 2), the present study showed that the maximum magnitude of average acceleration of the whole brain for front-forehead heading is 199.18 m/s^2 or 20.31 g with a contact time of 11.0

ms, and for top-forehead heading the maximum magnitude is 78.66 m/s^2 or 8.02 g with a contact time of 11.0 ms. For side-forehead heading the maximum magnitude is 200.11 m/s^2 or 20.40 g with a contact time of 11.0 ms. These values are still below the border line of fatal injury.

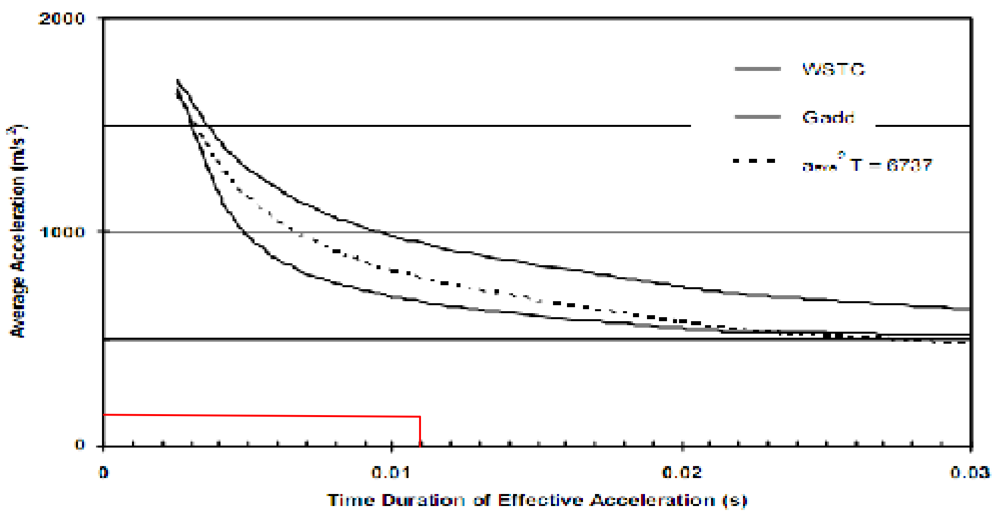


Figure 5.87: The results of the present study in Wayne State Tolerance Curve (red line)

The difference of the contact time between experiments and simulations (FEA) is 8.17% drop-test heading, 7.0% for front-forehead heading, 7.0% for the top-forehead heading and 1.0% for side-forehead heading. The difference of the ball speed between experiments and simulations (FEA) for the various tests is between 3.31% to 5.17%. These figures show that the difference is accepted and validated simulation models. Lastly, the results from this study are summarized in Table 5.5.

Table 5.6: Summary of the results of the speed of sepak takraw ball headings from FEA related to probability of concussion

Type of heading	Speed of ball (m/s)	HIC	HIP (kW)	Probability of concussion	
				HIC (%)	HIP (%)
Drop-test on the front-forehead	4.32	87.50	6.22	13	10
Front- forehead	13.58	210.15	11.36	42	39
	15	252.18	13.63	52	51
Top-forehead	13.58	180.17	10.74	34	32
	15	216.20	12.33	44	42
Side-forehead	10.95	190.32	11.17	36	34
	15	250.87	12.80	52	49

The different results of the percentages of HIC and HIP were due to the following constraints:

- The different distances from the point of impact to the base of the skull
- The different speeds of sepak takraw ball
- The different positions of heading

Therefore, based on Table 5.6, it can be seen that the top-forehead heading had a lower value of displacement of brain because its impact position was the nearest to the base skull and caused the acceleration to be lower compared to the others.

In addition, Figure 5.88 shows the HIC based on the Prasad-Mertz Curves. In sepak takraw, it was found that the HIC for the front-forehead heading is 252.18 (see the red dash lines) with the speed of sepak takraw ball at 15 m/s, where the probability of minor injury is 35%, the probability of moderate injury is 11 %, and the probability of major injury is 4%. Other headings also show results that are almost similar to the front-forehead heading.

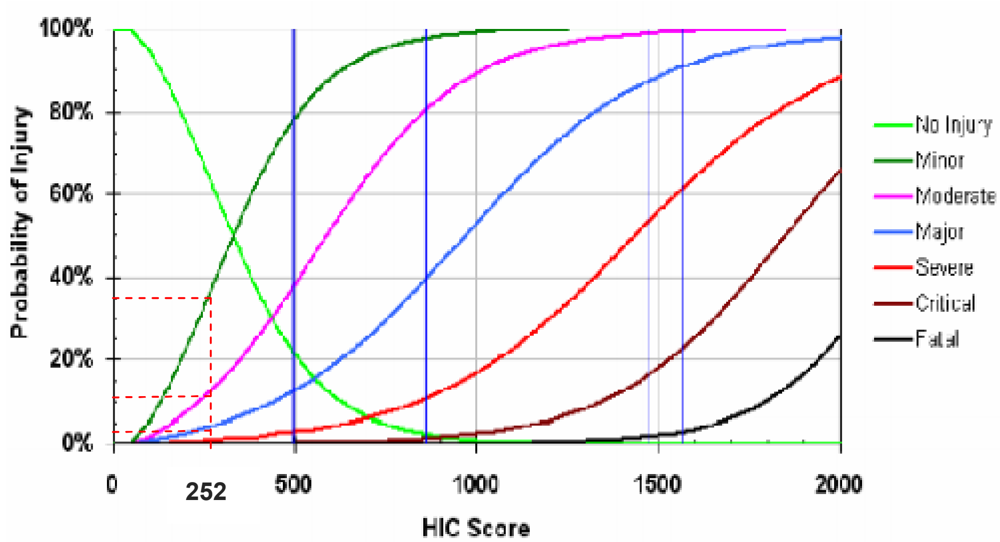


Figure 5.88: The results of the present study in Prasad-Mertz Curves (red dash lines)

Moreover, Figure 5.89 is the result based on Marjoux et al. (2007) on HIC of football cases. For the sepak takraw players in this study (see red line), it shows that the HIC is 2.52 with the speed of sepak takraw ball at 15 m/s. This is also found to be within the range of the football players in the study by Marjoux et al. (2007).

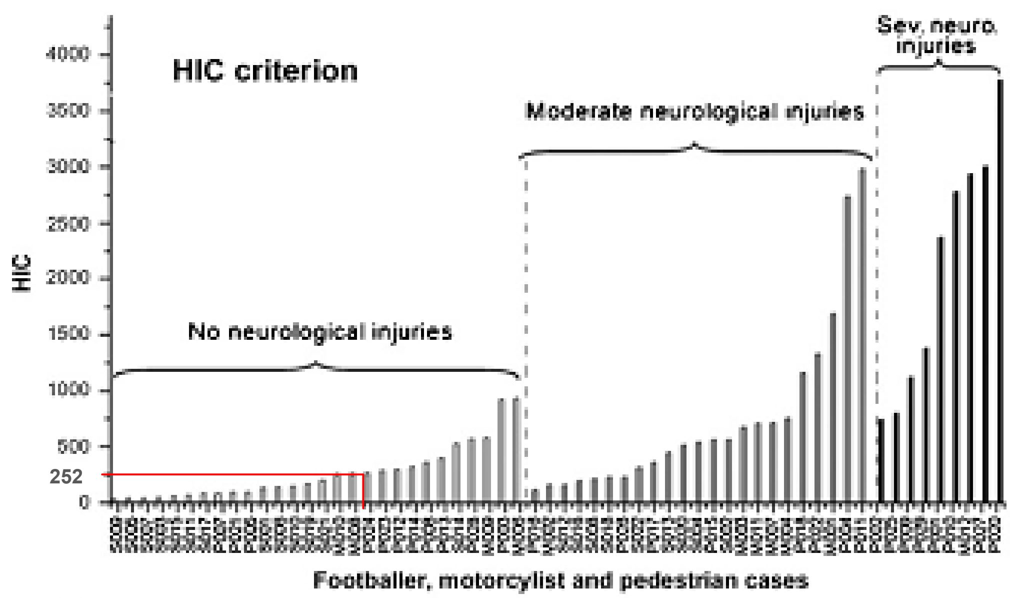


Figure 5.89: The results of the present study in histogram of HIC based on Marjoux et al. (2007) (red line is HIC for sepak takraw)

For HIP based on Marjoux et al (2007) (see Figure 5.90), the front-forehead heading for sepak takraw players 13.65 with the speed of sepak takraw ball at 15 m/s, which also shows that it is within the range of football players from cases in Marjoux et al. (2007).

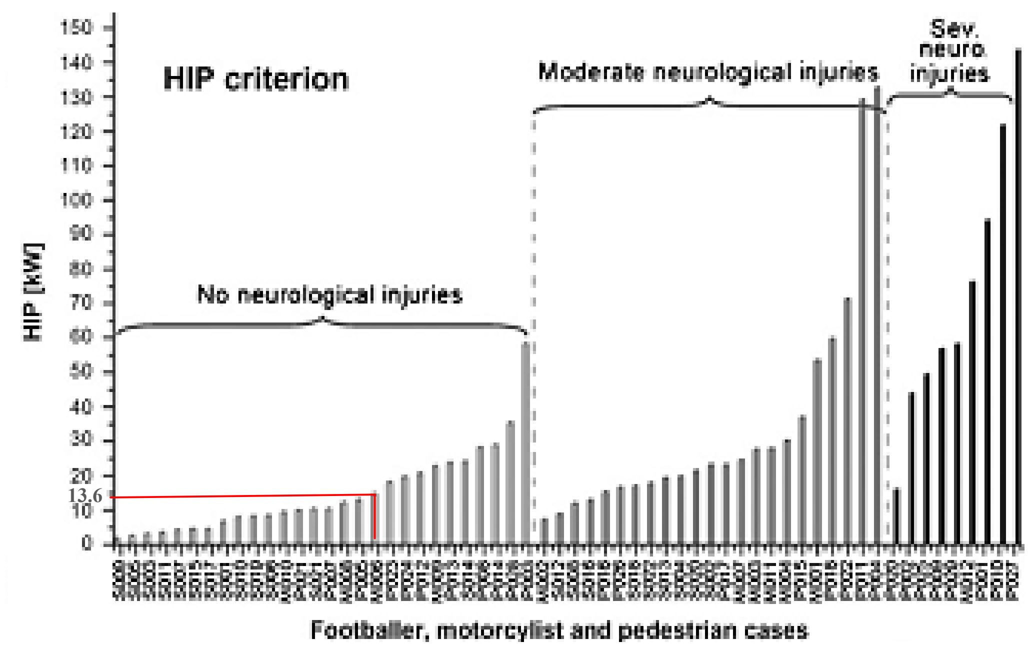


Figure 5.90: The results of the present study in histogram of HIP based on Marjoux et al. (2007) (red line is HIP in sepak takraw)

In conclusion, the results show that HIC and HIP occur on sepak takraw players. Even though the numbers are minor from this present study, thus, repetitions of headings in the future may further cause brain injury on the players.

RESULT OF EXPERIMENTAL STUDY

6.1 Introduction

This chapter presents the results from the experiment conducted on the impacts of sepak takraw ball with the head dummy. As mentioned earlier in CHAPTER 3, section 3.3.2.2, three brands of sepak takraw balls were selected for the experiments. The results obtained from the experiments were the impact forces, accelerations of brain gel, contact times of impact and speeds of ball during and after impact. Comparisons were made between the results of the experiments and the results of the FE analysis.

6.2 Comparison between Experiments and Finite Element Analysis

The finite element simulation of drop-test by using the skull dummy is shown in Figure 6.1. This section further provides the comparison of impact force, acceleration, contact time and speed of sepak takraw ball.

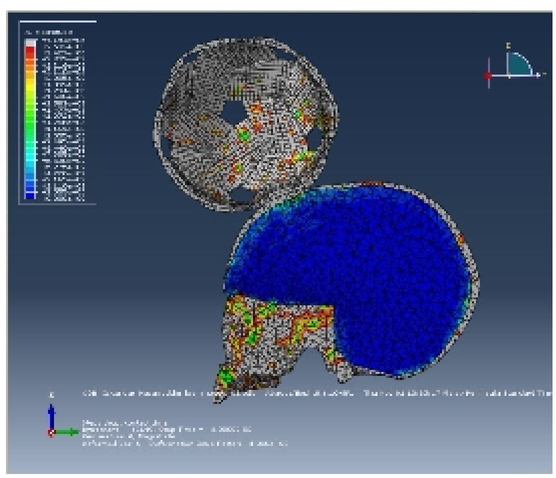


Figure 6.1: Finite element simulation of drop-test used skull dummy

6.2.1 Comparison of Impact Force

This section presents the results from the comparison of impact force from experiment (drop-test) and FE simulation. The experiment was conducted using 3 brands of sepak takraw balls, namely Marathon, Salim and Gajah Emas sepak takraw balls. The impact force analysis were conducted on all three and compared with each other. Thus, only the Salim brand was chosen for comparison with FE simulations because this was the sepak takraw ball used at the KFC-Utusan championship. This championship was the only event where the researcher was allowed to collect data of high speed video recordings by the organizer (see CHAPTER 3, Section 3.3.2.2.). Figure 6.2 shows the maximum impact force of the Marathon ball, which is 747.96 N at 0.004 sec (4 ms) and the contact time is 0.008 sec (8 ms).

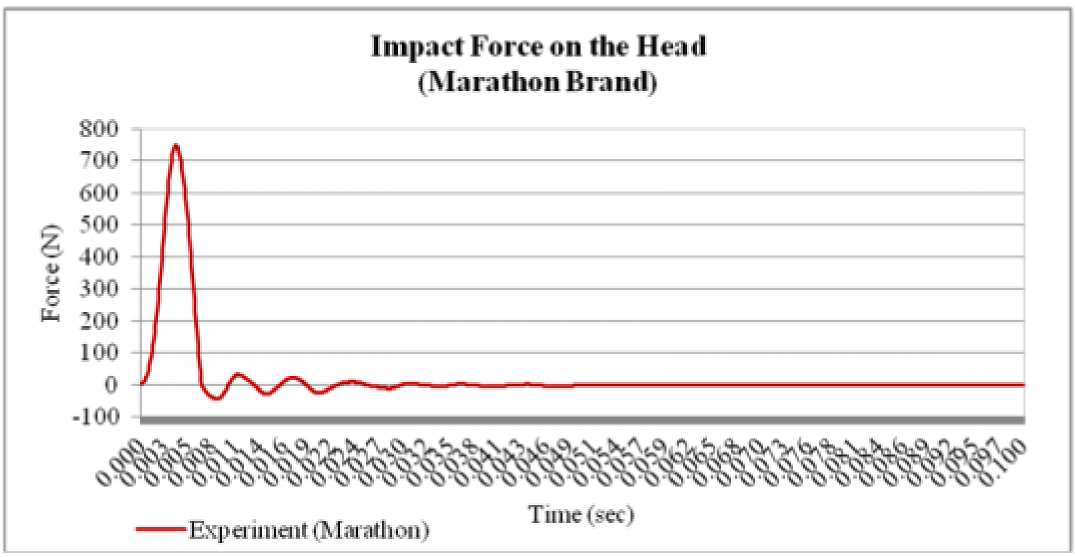


Figure 6.2: Impact force on the head dummy from Marathon sepak takraw ball

Figure 6.2 is the graph for the impact force on the head dummy of the Salim sepak takraw ball. It shows that the maximum impact force is 728.19 N at 0.0042 sec (4.2 ms) and the contact time is 0.008 sec (8 ms).

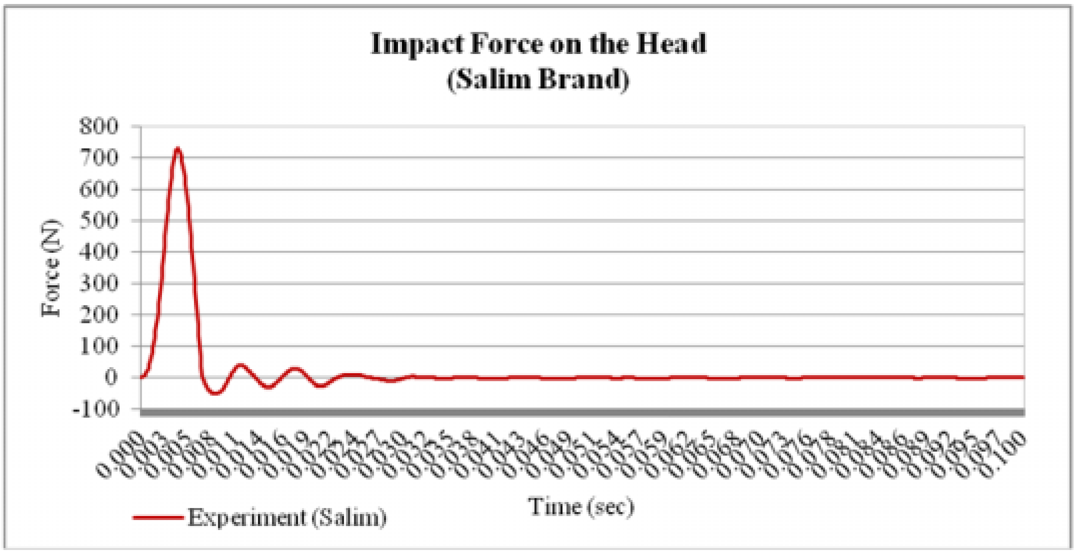


Figure 6.3: Impact force on the head dummy from Salim sepak takraw ball

Figure 6.4 presents the graph from the impact force on the head dummy of the Gajah Emas sepak takraw ball. It shows that the maximum impact force is 695.98 N at 0.0041 sec (4.1 ms) and the contact time is 0.008 sec (8 ms).

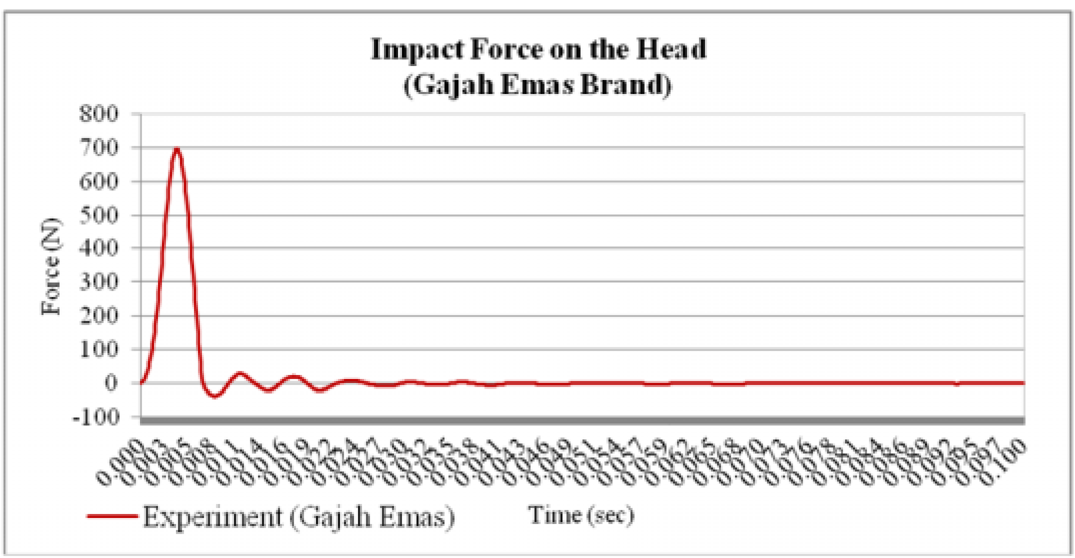


Figure 6.4: Impact force on the head dummy from Gajah Emas sepak takraw ball

From the three brands of sepak takraw balls, the highest impact force is exerted by the Marathon brand because it is heavier compared to the others.

Furthermore, a simulation of the impact force on the head model was also conducted. Figure 6.5 presents the impact force on the head from FEA simulation of the Salim sepak takraw ball. It shows that the maximum force is 745.60 N at time 0.0045 sec (4.5 ms). The contact time starts at 0.001 sec and ends at 0.0086 sec giving a total contact time of 0.0076 sec (7.6 ms).

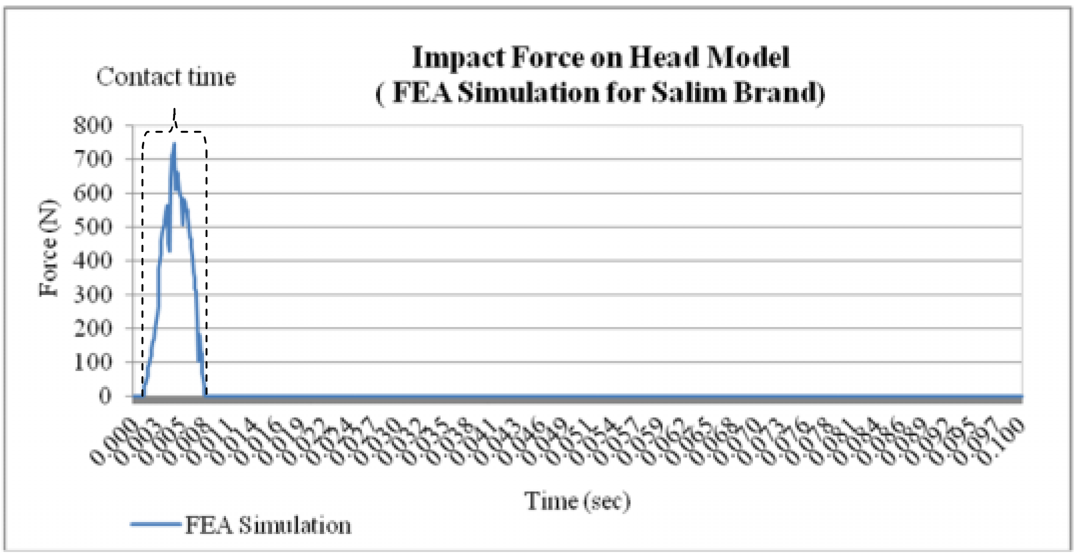


Figure 6.5: Impact force on head using FEA simulation with Salim takraw tall

A comparison of the FE simulation and experiment shows the difference is 5.0 % of the impact force on the head with the Salim brand (see previous Figure 6.3).

6.2.2 Comparison of Acceleration

This section provides a comparison the accelerations of the brain between FEA simulations and accelerometer sensor in the experiments.

Figure 6.6 below displays the graph of the acceleration of the brain from simulation and experiment in x-axis direction with the Salim brand. It shows that the maximum magnitudes in positive and negative directions of accelerations from FEA simulation in the x-axis are 34.51 m/s^2 and -38.11. The maximum magnitudes in positive and negative directions of accelerations from the experiment are 56.51 m/s^2 and - 74.42 m/s^2. From here, the differences are found to be 38.92 % for the positive direction and 48.79 % for the negative direction.

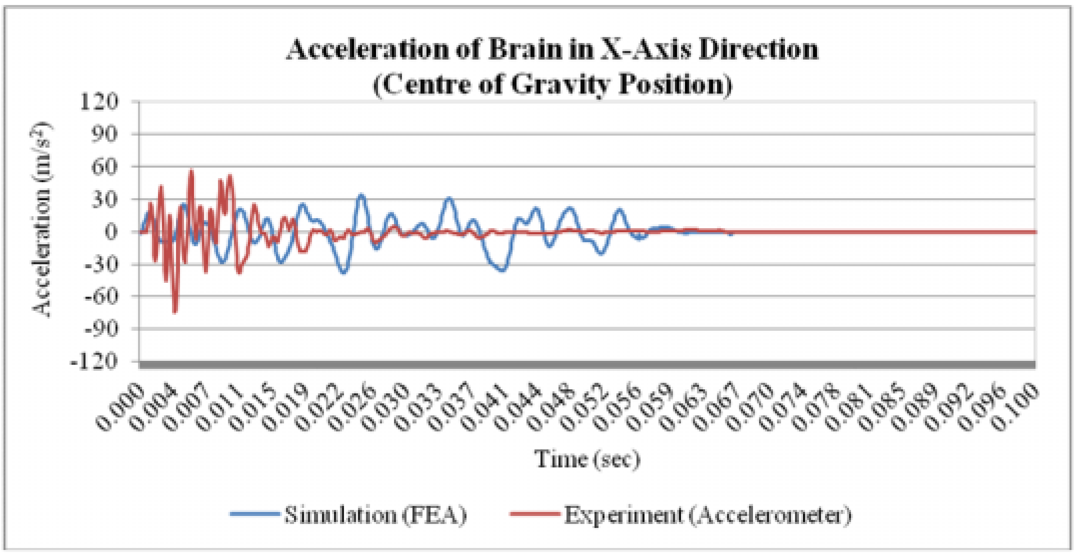


Figure 6.6: Comparison of accelerations between simulation and experiment in x-axis

Figure 6.7 presents a comparison of the accelerations of the brain between simulation and experiment in the y-axis with the Salim brand. It shows that the maximum magnitude positive and negative directions of accelerations from FEA simulation in the y-axis are 58.85 m/s^2 and -54.41 m/s^2. Then, the maximum magnitude in positive and negative directions of accelerations from the experiment in y-axis are

60.67 m/s^2 and -61.34 m/s^2. The difference are 3.0 % for the positive direction and 11.29% for the negative direction.

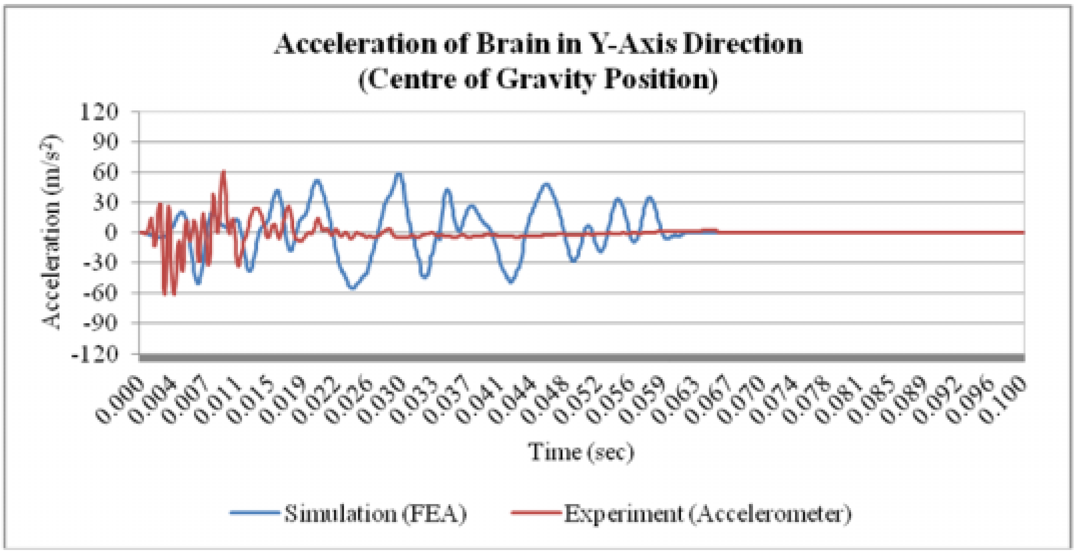


Figure 6.7: Comparison of accelerations between simulation and experiment in y-axis

A comparison of the acceleration of the brain between simulation and experiment in the z-axis of the Salim brand is shown in Figure 6.8. The maximum magnitudes in positive and negative directions of accelerations from FEA simulation in the z-axis are 85.41 m/s^2 and -105.33 m/s^2. Then, the maximum magnitudes in positive directions of accelerations from experiement in z-axis are 106.98 m/s^2 and -97.50 m/s^2. The difference are 20.16 % for the positive direction and 7.43 % for the negative direction.

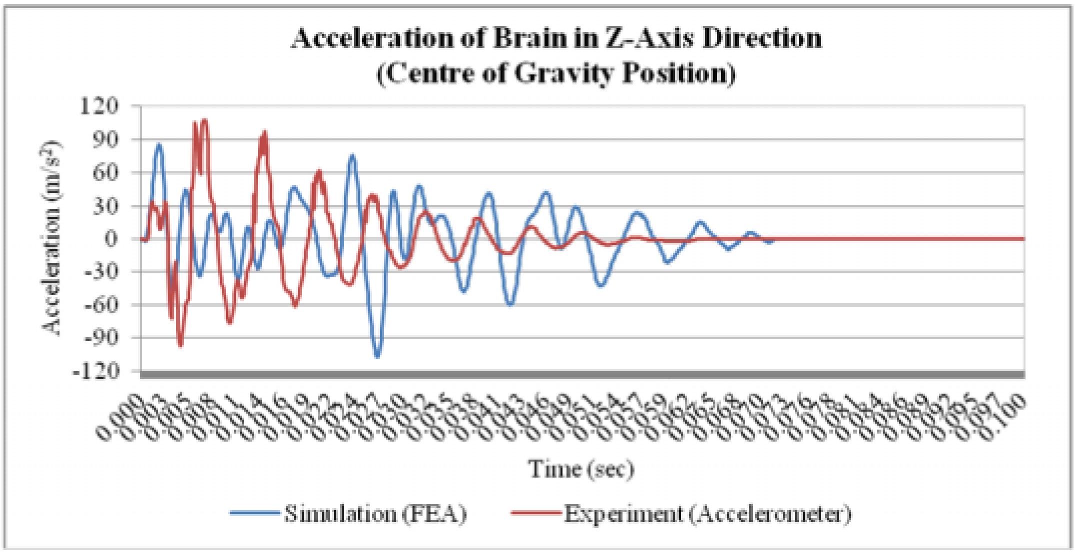
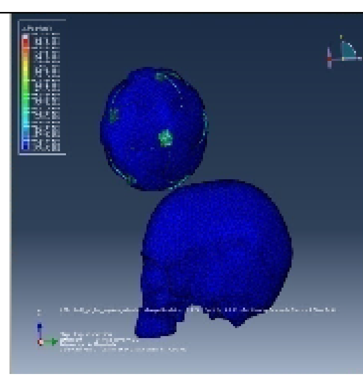
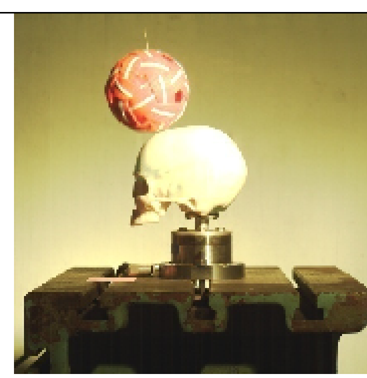


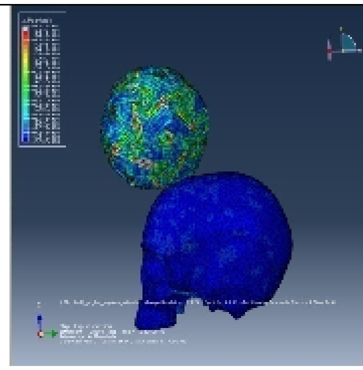
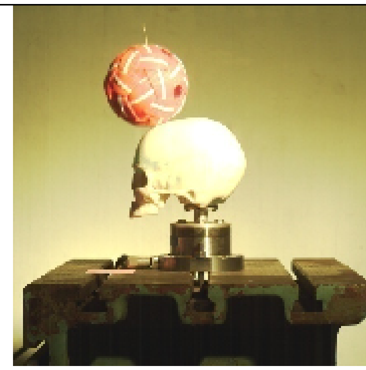
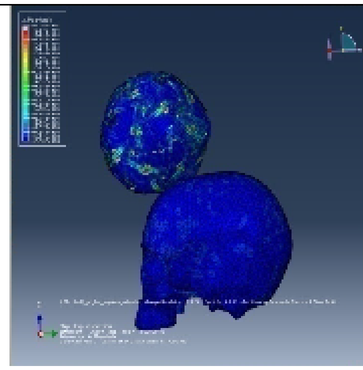
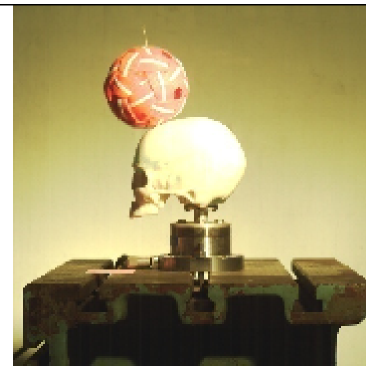
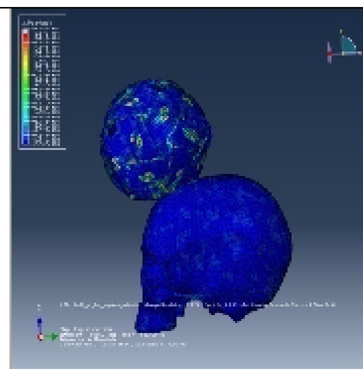
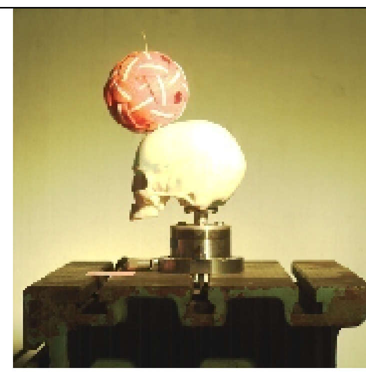
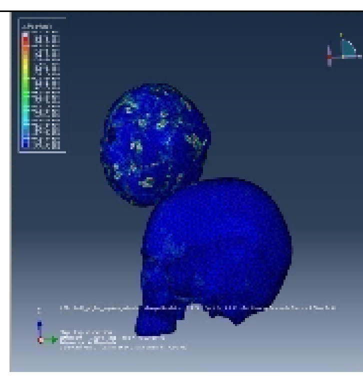
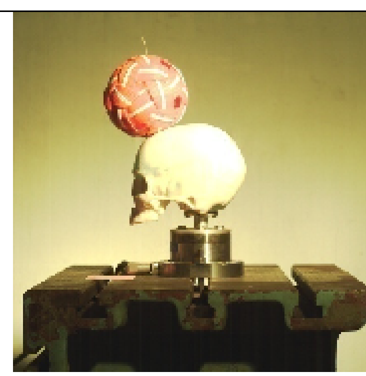
Figure 6.8: Comparison of accelerations between simulation and experiment in z-axis

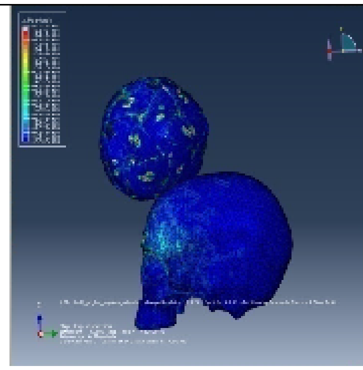
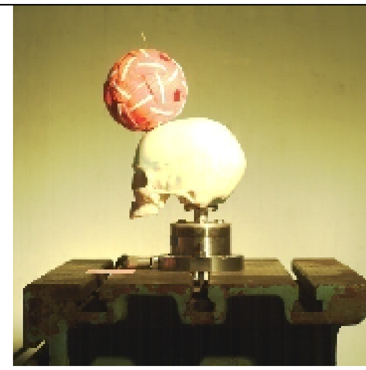
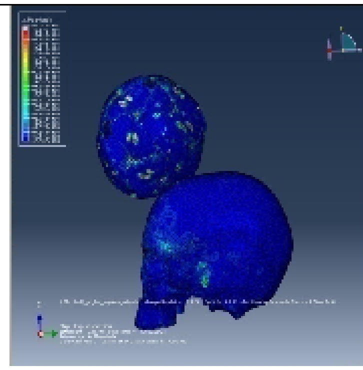
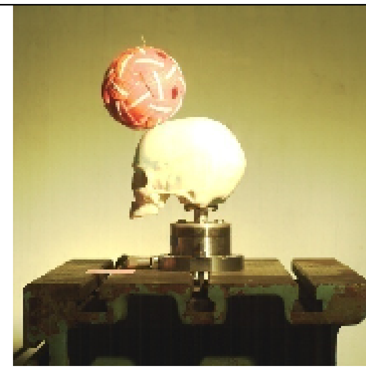
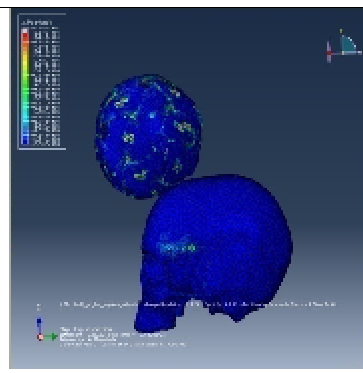
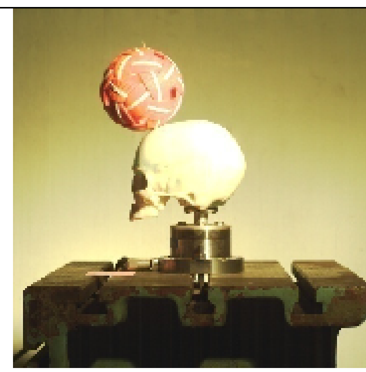
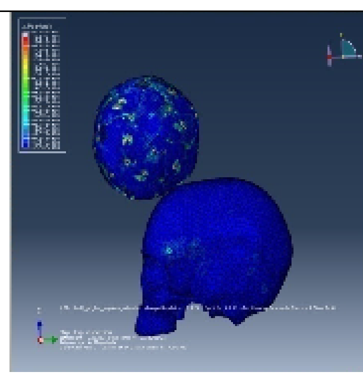
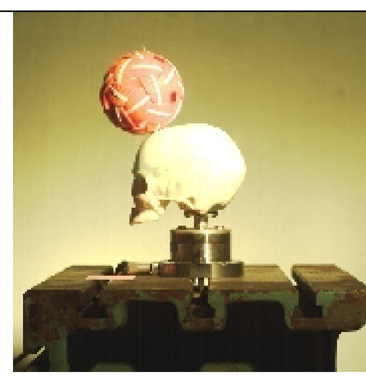
6.2.3 Comparison of Contact Time

This section shows the contact time between FE simulation and experiment from drop test in the laboratory of the Salim sepak takraw ball. Table 6.1 presents the related figures.

Table 6.1: Contact time between FE simulation and experiment using high speed camera

Time (ms)	FE Simulation	High Speed Camera
(0.0) Before heading		

1 first time of top-frontal heading		
2		
3		
4		

5		
6		
7		
End of drop-test dummy skull heading		
	The time is 7.6 ms	The time is 8 ms

The contact time in the simulation is 7.6 ms whilst from the experiment is 8 ms, the difference is of 5%.

6.2.4 Comparison of Sepak Takraw Ball Speed

A comparison between FEA and experiment of the speed of the centre of the sepak takraw ball during drop-test on the skull dummy heading is also conducted. As shown in Figure 6.10, the difference between experiment and FEA is 5.54 %.

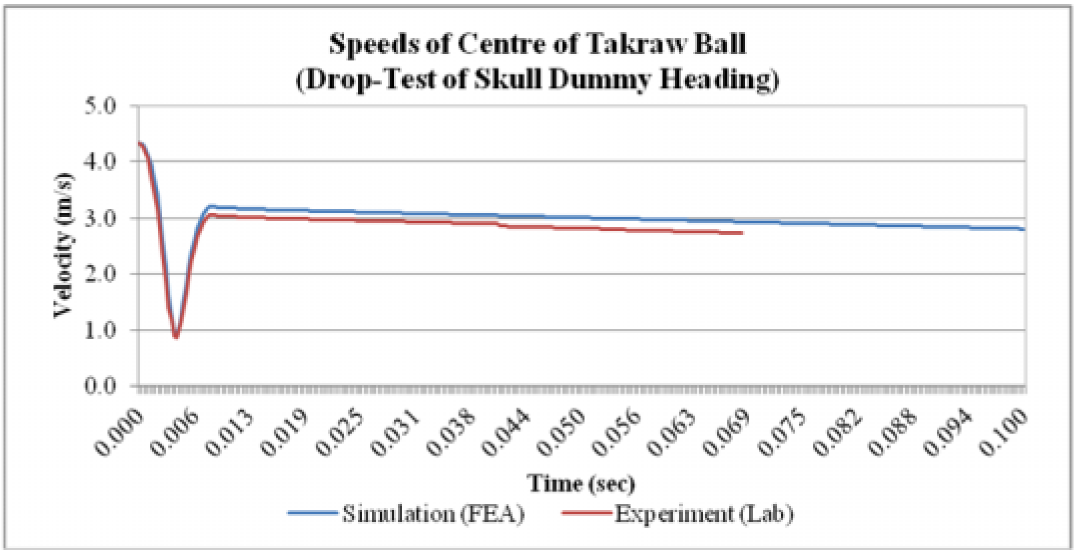


Figure 6.9: Comparison between FEA simulation and experiment on the speed of centre of sepak takraw ball for drop-test of skull dummy heading

6.3 Discussion and Summary

This chapter has presented the comparisons between the impact force on dummy head for each brand of the sepak takraw balls used in the experiments, namely Marathon, Gajah Emas and Salim. The marathon brand had more weight compared to the other two balls; its maximum average weight is 188.728 gram. Specifically it weighs 6.08% more than the average weight of the Salim ball and 6.16% more than the average weight of the Gajah Emas ball. Therefore, Marathon had the highest impact force, with a maximum of 747.96 N.

However, for comparisons with FE simulations, this study had only used the Salim brand due to data recording collection limitations as mentioned in Section 6.2.1.

The comparisons of the contact times and the speeds of the sepak takraw ball were also reported. It can be concluded that the results were valid as the difference for the impact force, contact time and speed of sepak takraw ball were roughly below 10%. The results from this chapter are concluded in Table 6.2 on the impact force and contact time from experiment, and Table 6.3 The difference from experiments and FE simulations.

Table 6.2: Result of Impact force and contact time from experiment

Brand of balls	Impact Force (N) (Experiment)	Contact time (ms)
Marathon	747.96	8
Salim	728.19	8
Gajah Emas	695.98	8

Table 6.3: The difference from experiments and FE simulations

<table>
<tr><td colspan="4">Salim brand</td></tr>
<tr><td colspan="3">Impact force (%)</td><td>5.0</td></tr>
<tr><td colspan="3">Contact time (%)</td><td>5.0</td></tr>
<tr><td colspan="3">Speed of ball during heading (%)</td><td>5.54</td></tr>
<tr><td rowspan="6">Accelerations</td><td rowspan="2">x-axis (%)</td><td>Positive direction</td><td>38.92</td></tr>
<tr><td>Negative direction</td><td>48.79</td></tr>
<tr><td rowspan="2">y-axis (%)</td><td>Positive direction</td><td>3.0</td></tr>
<tr><td>Negative direction</td><td>11.29</td></tr>
<tr><td rowspan="2">z-axis (%)</td><td>Positive direction</td><td>20.16</td></tr>
<tr><td>Negative direction</td><td>7.43</td></tr>
</table>

A comparison of the accelerations of the brain-gel and FE simulation showed some difference (see Figures 6.6 – 6.8). This due to the accelerometer sensor having cables attached it, but in the FE simulation model of the brain it is just a node. The cable, prevented free movement of the sensor, causing the acceleration to settle more rapidly compared to the simulation where the node is free.

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The findings of this study had largely given an overview of the head injury criterion (HIC) and head impact power (HIP) from sepak takraw players' collisions with the sepak takraw balls on their head at three locations, namely front-forehead, top-forehead, and side-forehead. These were done through FE simulations and experiments. Section 5.6 have discussed the findings in relation to the HIC and HIP from previous studies, and the numbers of this present study do show a possibility for the sepak takraw players to experience MTBI caused by the collisions of the sepak takraw balls with their heads. The results from this study are outlined as follows.

For HIC, the probability of concussion from the drop-test of sepak takraw ball for the low speed at the front-forehead heading was 13%. Thus from the experiment with data from the championship, the probabilities were found to be higher at higher speeds, specifically, 42 % for front- forehead heading, 34 % for top-forehead heading and 36% for side-forehead heading.

For HIP, the probability of concussion from the drop-test of sepak takraw ball for the low speed at the front-forehead heading was 10%. Thus similarly with HIC, the results from the experiment with data from the championship, the probabilities were found to be higher at higher speeds, specifically, 39 % for front- forehead heading, 32 % for top-forehead heading and 34% for side-forehead heading.

The discovery above is also substantiated by the results from the interviews with the players. From the interviews regarding MTBI, after headings, 88% of the subjects felt headaches, 80% regularly forgot where they put things (everyday), 68% felt nervous before starting a game, 65% had tears coming out of their eyes, 64% felt emotional, 68% heard sound of droning, 84% felt their eyes sensitive toward bright lights and 67%

felt unbalanced. The correlation between the HIC and HIP percentages on the probability of concussions for these players with the percentages from the interviews regarding MTBI is immense. It can be asserted that the players had experienced MTBI especially as most of them (at 78%) were not wearing any headbands for possible head protection.

This present study assumed that repetition of collisions by the Sepak Takraw players may continue to occur to further cause higher probabilities of MTBI later in their life. Consequently, this study further suggests the use of headband to reduce the possibilities of MTBI for the subjects, especially since they are still active players in the game.

7.2 Major Contributions

This research has contributed some understanding on the effects of sepak takraw balls on the players, above all on their collisions with the head that can cause MTBI. Because the results of comparisons of the impact force, contact time and speed of the sepak takraw ball had similarities above 90%, therefore the FE model of the head applied in this study is considered valid. Therefore, the existing model could be used for further studies on head impacts of sepak takraw players. The anthropometric data measurements which were obtained for this study could also be used by future researchers as a base to guide possible and appropriate designs of headband crafted for Malaysian sepak takraw players, specifically for the killer players as they perform more headings compared to the others players.

7.3 Recommendations for Future Work

To reduce the MTBI revealed in the findings, this study offers some recommendations possibly for better improvement of the players' health. Among them are to design sepak takraw balls with friendlier materials for the human head to reduce possible brain injuries on the players. The International Sepak Takraw Federation (ISTAF) has also suggested the use of headbands for players as one of the rules to be applied in this game, especially for killer players. Lastly, the coaches of Sepak Takraw should consider the findings where the killer could not perform better spikes after hard headings; therefore the employment of double killers in the game is suggested to avoid point lost in the games.

Finally, this initial study is limited to the calculation of HIC and HIP probabilities of concussions from Malaysian sepak takraw players. It further recommends future work using a more complete model of a brain to examine specifically the injury details that may occur after impact.

REFERENCES

AAAM, AIS (2005). *The injury scale (eds. Gennalli T and Wodzin E).* New York: American Association for Automotive Medicine.

Al-Bsharat A., Hardy W., Yang K., Khalil T., Tashman S., & King A. (1999). Brain/skull relative displacement magnitude due to blunt head impact: new experimental data and model. *Proceedings of the 43rd Stapp Car Crash Conference, October.*

Arbogast K.B & Margulies S.S. (1999). A fiber-reinforced composite model of the viscoelastic behavior of the brainstem in shear. *Journal Biomech.* 32:865–870.

Ahmad N., Taha Z., Tuan Ya S. Y. M. T. & Hasanuddin I.(2012), Finite Element Simulation of Takraw Balls and Their Impact on a Flat Surface, *Movement, Health & Exercise,* a sport journal by Ministry Higher Education, Malaysia, 1(1), 1-9.

Ahmad N., Taha Z., Ujihashi S., & Tanaka K., (2009) An experimental study of the impact of a sepak takraw ball on a flat surface, pages 447-452. *The Impact of technology on Sport III, Chapter: Design. RMIT University Publisher*.

Alem N., (1974) *A discrete-parameter head injury model*. PhD thesis, The University of Michigan.

Atha J., Yeadon M., Sandover J., Parsons K., (1985) The damaging punch, *Br Med. journal* (Clin Res Ed), Vol. 291 (6511), page 1756-1757..

Bandak F. & Eppinger R., (1994) A three-dimensional finite element analysis of the human brain under combined rotational and translational acceleration. In *Proceedings of the 38th Stapp Car Crash Conference*, pages 145–163.

Becker E., (1972) Measurement of mass distribution parameters of anatomical segments. In *Proceedings of the 16th Stapp Car Crash Conference*, pages 160–185,.

Biasca N., Lovell M., Collins M., Jordan B., Matser E., Weber J., Slemmer J., Piccininni P., Maxwell W., Agosti R., Wirth S., & Schneider T., (2006a) Die unerkannte hirnverletzung im sport: das leichte schädel-hirn-trauma und seine folgen, *Teil 1, Schweiz, Med. Forum*, vol. 6 page 93-96..

Biasca N., Lovell M., Collins M., Jordan B., Matser E., Weber J., Slemmer J., Piccininni P., Maxwell W., Agosti R., Wirth S., & Schneider T., (2006b) Die unerkannte hirnverletzung im sport: das leichte schädel-hirn-trauma und seine folgen, *Teil 2, Schweiz, Med. Forum*, vol. 6 page 121-128.

Brands D., (2002). *Predicting brain mechanics during closed head impact: numerical and constitutive aspects*. PhD thesis, Technische Universiteit Eindhoven, Eindhoven, The Netherlands,

Bridger R. S. (1995) *Introduction to Ergonomics*, McGraw-Hill International Edition, Singapore.

Chaffin, D. B., & Gunnar B. J. Andersson., (1999) *Occupational Biomechanics (3rd ed.)*. John Willey & Son, Inc, USA.

Chandler R., Clauser C., McConville J., Reynolds H., & Y. J. W., (1975) Investigation of inertial properties of the human body. Technical Report DOT HS-801 430, US Department of Transportation, Washington D.C.

Chen Y., Sutton B., Conway C., Broglio P. S., & Ostoja-Starzewski M., (2012) Brain deformation under mild impact: magnetic resonance imaging-based assessment and finite element study, *International Journal of Numerical Analysis And Modeling*, Series B vol. 3 (1), 20–35,.

Cheng L., Rifai S., Khatua T., & Piziali R., (1990) Finite element analysis of diffuse axonal injury. *In Vehicle Crashworthiness and Occupant Protection in Frontal Collisions*, pages 141–154, Society of Automotive Engineers.

Chu C., Lin M., Huang H., & Lee M.. (1994) Finite element analysis of cerebral contusion. *Journal of Biomechanics*, 27(2):187–194.

Claessens M., Sauren F., & Wismans J., (1997) Modeling of the human head under impact conditions: a parametric study. In *Proceedings of the 41st Stapp Car Crash Conference*, pages 315–328.

CPSC, (1995) "*Soccer Head Injuries,* Calendar Year 1995 to 11-30-02," National Electronic Injury Surveillance System (NEISS).

Delaney J. S. & Lacroix V. J., et al., (2002) "Concussions Among University Football and Soccer Players," *Clin J Sport Med,* 12(6):331-8.

DeVellis, R.F. (1991) *Scale Development: Theory and Application*. SAGE publications Newbury Park, London, Pages 24-33.

Dimensionprinting.com*, Stratasys, Inc.*14950 Martin Drive, Eden Prairie, MN 55344, USA.

Eco-Med Pharmaceutical Inc. 7050, Bramalea Road Unit C58, Mississauga, ON L5S 1S9, Canada.

Federal Motor Vehicle Safety Standard (FMVSS) 208 (1999), *Title 49 Code of Federal Regulations (CFR)*, Department of Transport, National Highway Traffic Safety Administration, October.

Fehrenbach M. & Herring S., (2002) *Illustrated anatomy of the head and neck*. Saunders, Philadelphia, pg. 86.

Fifa.com

Gadd, C.W., (1966) "*Use of Weighted-Impulse Criterion for Establishing Injury Hazard"*, Proceedings of the Tenth Stapp Car Crash Conference, Holloman Airforce Base, New Mexico, Nov, , Society of Automotive Engineers, pg. 164.

Gennarelli T. & Thibault L., (1982) Biomechanics of acute subdural hematoma. *Journal of Trauma*, 22:680–686.

Gilchrist M., O'Donoghue D., & Horgan T., (2001) A two-dimensional analysis of the biomechanics of frontal and occipital head impact injuries. *International Journal of Crashworthiness*, 6(2), 253–262.

Gross C.M, Goonetilleke R.S., Menon K.K. Banaag J.C.N. & Nair C.M. (1994) "*The Biomechanical Assessment and Prediction of Seat Comfort"*. In hard facts and soft machines: The Ergonomics of seating Taylor.

Gurdjian, E.S., Webster, J.E.,& Lissner, H.R., (1955) "Observations on the Mechanism of Brain Concussion, Contusion and Laceration", Surg. Gynec & Obstet 101: 680-690.

Ho J., Holst V. H. & Kleiven S. (2009) Automatic generation and validation of patient-specific finite element head models suitable for crashworthiness analysis, *International Journal of Crashworthiness* Vol. 14, No. 6, pages 555–563.

Hosey R. & Liu Y., (1982) A homeomorphic finite element model of the human head and neck. In R. Gallagher, B. Simon, P. Johnson, and J. Gross, editors, *Finite elements in biomechanics*, John Wiley & Sons, 379–401.

Huang H., Lee M., Chiu W., Chen C., and Lee S., (1999) Three-dimensional finite element analysis of subdural hematoma. *The Journal of Trauma: Injury, Infection, and Critical Care*, 47(3):538–544.

Huang H., Lee M., Lee S., Chiu W., Pan L., and Chen C., (2000) Finite element analysis of brain contusion: an indirect impact study. *Medical & Biological Engineering & Computing*, 38(2):253–259.

Humanbody3d.com

Hunter R. (1999) Skiing injuries, *Am journal sports injury*, vol. 27, page 381-389.

Itabashi H. H., (2007) *"Blunt force head injury" Forensic neuropathology - a practical review of fundamentals*, Academic Press.

Junge A., Langevoort G., Pipe A., Peytavin A., Wong F., Mountjoy M., Beltrami G., Terrell R., Holzgraefe M., Charles R., & Dvorak J., (2006) Injuries in team sport tournaments during the 2004 Olympic Games, *Am Journal Sport Med*. Vol.34(4), page 555-576..

Khalil T. & Viano D. (1982) Critical issues in finite element modeling of head impact. In *Proceedings of the 26th Stapp Car Crash Conference*, 87–102.

Kleiven S., (2003) Influence of Impact Direction on the Human Head in Prediction of Subdural Hematoma, *Journal of Neurotrauma,* Vol. 20, Number 4, © Mary Ann Liebert, Inc.

Kroemer, K. H. E., & Kroemer, H. B., (1993) "*Ergonomics: How to Design for Ease and Efficiency*", 1st ed, New Jersey: Prentice Hall.

Kuijpers A., Claessens M., & Sauren A., (1995) The influence of different boundary conditions on the response of the head to impact: a two dimensional finite element study. In F. Bandak, R. Eppinger, A. Ommaya, and M. Liebert, editors, *Traumatic Brain Injury Bioscience and Mechanics*, pages 197–206. New York.

Lau, I.V., and Viano, D.C. (1986) "The Viscous Criterion: Bases and Applications of an injury Severity Index for Soft Tissues", *Proceeding of 30th Stapp Car Crash Conference* (P-189), pp.123-142, SEA Technical Paper No.861882, Society of Automotive Engineers.

Levy A., Hawkes A., Hemminger L, & Knight S., (2002) An analysis of head injuries among skiers and snowboarders, *journal trauma*, vol. 53(4), page 695-704.

Lipton, M., (2011) Heading a ball Trigger Brain Damage, *Annual meeting of the Radiological Society of North America*. Radiological Society of North America, Dec.

Lopez P. F. L., Beldia D. M., Pangan J. R., & Cabag C. R., (1993) Physical Education Heath and Music. *Rex Book Store, Philippines*. p.91.

Lovell, M. R. & Collins, M.W. (1998) Neuropsychological assessment of the college football player. *Journal Head Trauma Rehabilitation*, 13(2), 9-26.

Marjoux D., Baumgartner D., Deck C.,& Willinger R., (2007) Head injury prediction capability of the HIC, HIP, SIMon and ULP criteria. *Accident Analysis and Prevention Journal*., p.1135-1148.

Martin, T. P & M. B. Pongratz, (1974) Validation a mathematical model for correction of photographic perspective error in R. C. Nelson and C. A More-house Eds. *Biomechanics IV*, university park press, Baltimore, Md. pages 469-475.

McConville J., Clauser C., Churchill T., Cuzzi J., & Kaleps I., (1980) *Anthropometric relationships of body and body segment moment of inertia*. Technical Report AFAMRL-TR-80-119, Wright-Patterson Air Force Base, Ohio.

McIntoch A., McCrory, (2005) Preventing head and neck injury, *Br journal Sport Med*, vol. 39, page 314-318.

Miller, R.T., Margulies, S.S., Leoni, M., Nonaka, M., Chen, X., Smith D.H., & Meaney D.F, (1998) Finite element modeling approaches for predicing injury in an experimental model of severe diffuse axonal injury, in: *42nd Stapp Car Crash Conf. SAE paper no. 983154.* Society of Automotive Engineers, pps. 155– 167.

Morrison III. B., Cater H., Wang C., Thomas F., Hung C., Ateshian G., and Sundstrom L., (2003) A tissue level tolerance criterion for living brain developed with an in vitro model of traumatic mechanical loading. *Stapp Car Crash Journal*, 47:93–105.

National Highway Traffic Safety Administration (NHTSA), Department of Transportation, (1997). FMVSS201, *Head Impact Protection*, 49 CFR §571.201.

National Operating Committee on Standards for Athletic Equipment (NOCSAE), (1997) doc. 002-96, *Standard Performance Specification for Newly Manufactured Football Helmets*, January.

Naval biodynamics laboratory. (1988) *Anthropometry and mass distribution for human analogues*, Vol I: Military Male Aviators, P.O. Box 29407 New Orleans, UI 70189-0407.

Newman, J.A (1998). "Kinematics of Head Injury – An Overview", Frontiers of Head and Neck Trauma: Clinical and Biomechanical, *IOS Press Inc*., Burke, Virginia, pp. 200-214.

Newman J. A, Shewchenko N., Welbourne E., (2000) A Proposed New Biomechanical Head Injury Assessment Function - the maximum Power Index, SAE paper 2000-01-SC16, *Stapp Car Crash Conference*, vol.44.

Ommaya, (1984) Biomechanics of head injury, in biomechanics of trauma, Eds. Nahum, Melvis, Appleton-century-crofts, Norwalk.

Ontario Neurotrauma Foundation, (2009) G*uidelines of mild traumatic brain injury and persistent symptoms,* Toronto, Ontario, Canada.

Padgaonkar A., Krieger K., and King A., (1975) Measurement of angular acceleration of a rigid body using linear accelerations. *Journal of Applied Mechanics*, 42:552–556.

Park C. and Hyun D., (2004) Apoptotic change in response to magnesium therapy after moderate diffuse axonal injury in rats. *Yonsei Medical Journal*, 45(5):908–916.

Pellman E., Powell J., Viano D., Casson I., Tucker A., Feuer H.,Waeckerle J., Robertson D., (2003) Concussion in professional football: epidemiological features of game injuries and review of the literature-part 3, Neurosurgery, vol. 54 (1), page 81-94.

Prasad P, Mertz HJ, (1985) The position of the United States delegation to the ISO working 6 group on the use of HIC in the automotive environment. *SAE Paper# 851246 Society of Automotive Engineers*, Warrendale PA, USA.

Phillips C. A., (2000) Human Factor Engineering, John Wiley & Sons, Inc.

Pike J. (1990) *Automotive safety: anatomy, injury, testing and regulation*. Society of Automotive Engineers, Warrendale, PA.

Price D., Jones R, Harland A & Hawkings P. (2007) Soccer ball dynamic force measurement and modelling *Journal of Sports Science and Medicine, Suppl. 10.* 48-49.

Ruan J., Khalil T., and King A., (1993) Finite element modeling of direct head impact. In *Proceedings of the 37th Stapp Car Crash Conference*, pages 69–81.

Ruan J., Khalil T., and King A., (1991) Human head dynamic response to side impact by finite element modeling. *Journal of Biomechanical Engineering*, 113:276–283,.

Santoso S. (2001) *Statistik Non Parametrik, Buku latihan SPSS,* Elex Media Komputindo, Jakarta.

Schmitt K-U., Niederer F P., Muser H. M. and Wals F., (2007) *Trauma Biomechanics - Accidental injury in traffic and sport.* 2nd edition, Springer.

Shepard S., (2007) *Head trauma*. eMedicine.com, March 16.

Shojaati M. (2003) *Correlation between injury risk and impact severity index ASI*, 3rd Swiss Transport Research Conference.

Shorten M. R., (2009) Estimated Risk of Head Injury on Artificial Turf Surfaces with Brock Underlayment, *BioMechanica,* LLC 425 SE Ninth Ave. Portland, Oregon 97214, USA.

Smith T., Bishop P., Wells R., (1988) Three dimensional analysis of linear and angular accelerations of head experienced in boxing, proceeding *IRCOBI conference*, page 271-285.

Smith M., Dyson R., Hale T., Janaway L., (2000) Development of boxing dynamometer and its punch force discrimination efficacy, J*ournal of Sport Science*, vol. 18(6), page 445-450.

Spiotta A. M., Bartsch A. J., Benzel E. C., (2011) Heading in Soccer: Dangerous Play? *Congress of Neurological Surgeons*, Vol. 70, No. 1 pages 1- 11.

Taha. Z, Iskandar & Hilma (2008) A study of the impact of sepak takraw balls on the head**.** *International Journal of Sports Science and Engineering***,** Vol. 02 (2), 107-110.

Takhounts E., Eppinger R., Campbell J., Tannous R., Power E., and Shook L., (2003) On the development of the SIMon finite element head model. *Stapp Car Crash Journal*, 47:107–133.

Ueno K., Melvin J., Li L., and Lighthall J., (1995) Development of tissue level brain injury criteria by finite element analysis. *Journal of Neurotrauma*, 12:695–706.

Usman J, Wan Abas W. A. B., Rambely A. S., and Abu Osman N. A., (2002) A comparative study on kinematics parameters between the sepak kuda serve and the sepak sila serve in sepak takraw. In XXth *International Symposium on Biomechanics in Sports - ISBS, Caceres, Spain; July 2002, pg.191.*

Usman J. & Wan Abas W. A. B., (2004) A comparative analysis on selected kinematics parameters between the "sepak kuda" serve and the "sepak sila" serve in sepak takraw. *International Society of Biomechanics in Sports (ISBS) and the Faculty of Health Sciences, University of Ottawa*. 322-325.

Utusan Malaysia newspaper of date 20/12/2007

Versace, J., (1971) "A Review of the Severity Index", *Fifteenth Stapp Car Crash Conference Proceedings*, Sociey of Automotive Engineers, pp 771-796.

Walilko T., Viano D., Bir C., (2005) Biomechanics of the head for Olympic boxer puncher to the face, *Br journal sport med*, vol. 39, page 710-719.

Ward C. and Chan M., (1980) Intracranial pressure - a brain injury criterion. In *Proceedings of the 24th Stapp Car Crash Conference*, pages 163–185.

Wasserman J. and Koenigsberg R., (2007) Diffuse axonal injury, *eMedicine.com*, March 13.

Whittle M. W., (1995) *Musculoskeletal Applications of Three-Dimensional Analysis. In Three-Dimensional Analysis of Human Movement*, ed Paul Allard, Ian A. F. Stokes, & Jean-Pierre Blanchi, (pp. 295 – 309). United States of America: Champaign, IL Human Kinetics.

Willinger R. and Baumgartner D. (2003) Human head tolerance limits to specific injury mechanisms. *International Journal of Crashworthiness*, 8(6), 605–617.

Willinger R., Taleb L., Kopp C.M. (1995) Modal and temporal analysis of head mathematical models, J. Neurotrauma 12 (4), 743-754.

Willinger, R., Taleb, L., Pradoura, P.,(1995) Head biomechanics from the finite element model to the physical model. In: ProceedingsIRCOBI, Brunnen.

www.bangkok.com/sport-sepak-takraw

Yogonandan N., Pintar F.A., Sances A. Walsh ER., Ewing C.L., Thomas D.J., Snyder R.G., (1994) *Biomechanics of Skull Fracture.* Traumatic Brain Injury, Liebert Inc. Publishers, 227- 236.

Yen K, Metzl J, (2000) Sport-specific concerns in the young athlete: baseball, *Pediatric emergency care*, vol. 16, page 215-220.

Zarzyn T., Finch C, McCrory P. (2003) A 16 year study of injuries to professional boxers in the state of Victoria Australia, *Br. Journal of sport med*. vol. 36, page 270-275.

Zatsiorsky V. and Seluyanov V., (1983) The mass and inertia characteristics of the main segments of the human body. In H. Matsui and K. Kobayashi, editors, *Biomechanics VIII-B*, pages 1152–1159. Human Kinematics Publishers, Champaign, Illinois.

Zhang L., Yang K., and King A., (2001) Comparison of brain responses between frontal and lateral impacts by finite element modeling. *Journal of Neuratrauma*, 18(1):21–30.

Zhang L., Yang K., Dwarampudi R., Omori K., Li T., Chang K., Hardy W., Khalil T., and King A., (2001) Recent advances in brain injury research: a new human head model development and validation. *Stapp Car Crash Journal*, 45:369–394.

Zhang L., Yang K., and King A, (2004), A propose injury threshold for mild traumatic brain injury, *journal of biomechanics engineering*, vol. 126, page 226-236.

Zhang M.R, Red S.D., Lin A.H., Patel S.S. & Sereno A.B. (2013) Evidence of Cognitive Dysfunction after Soccer Playing with Ball Heading Using a Novel Tablet-Based Approach. PLoS ONE vol.8 (2), journal.pone.0057364.

Zhou, C., Khalil, T. B., & King, A. I., (1996) A 3D human head finite element model for impact injury analysis, *Symp. Proc. Prevention through Biomechanics*, Wayne State University, 137-148.

Zomeren V. A. & Brouwer W. (1994) *Clinical Neuropsychology of attention*. Oxford University Press, New York.

Zou H., (2007) Analysis and Modeling of the Biomechanics of Brain Injury under Impact, *PhD Dissertation*, Ohio State University.

APPENDIX A

Sepak Takraw Sport

Outcomes Questionnaire

Developed by:

Sport Engineering Group

Centre for Product Design & Manufacturing (CPDM)

Faculty of Engineering

University of Malaya

Kuala Lumpur

Introduction

Today's Date: / /

Thank you for completing this questionnaire!

This questionnaire will help us to better understand your general health and performances related to sepak takraw sport.

Your completion of this questionnaire is completely voluntary and your responses will be held in the strictest confidence.

Please answer every question. Some questions may look like others, but each one is different.

There are no right or wrong answers. If you are not sure how to answer a question, just give the best answer you can. You can make comments in the margin. We do read all your comments, so feel free to make as many as you wish.

Player Information / *Informasi Permain* (**Section A**)

<table>
<tr><td>1</td><td>Name

Nama</td><td colspan="5"></td></tr>
<tr><td>2</td><td>Area of Group

Kawasan Kumpulan</td><td colspan="2"></td><td>Date of Birth

Tarikh Lahir</td><td colspan="2"></td></tr>
<tr><td>3</td><td>E-mail (Optional)</td><td colspan="5"></td></tr>
<tr><td>4</td><td>Phone (Optional)</td><td colspan="5"></td></tr>
<tr><td rowspan="2">5</td><td rowspan="2">Playing Position

Posisi Permainan</td><td colspan="5">Can choose more than one

Boleh pilih lebih dari satu</td></tr>
<tr><td colspan="2">Feeder</td><td colspan="2">Tekong</td><td>Killer</td></tr>
<tr><td rowspan="2">6</td><td rowspan="2">Player Level

Peringkat Permain</td><td colspan="5">Can choose more than one

Boleh pilih lebih dari satu</td></tr>
<tr><td>School / Institution</td><td>Club / Company</td><td>State / Territory</td><td>National</td><td>Others (please specify)</td></tr>
<tr><td>7</td><td colspan="3">Since in what age do you start playing sepaktakraw?

Sejak umur berapa anda mula bermain sepak takraw?</td><td colspan="3"></td></tr>
<tr><td>8</td><td colspan="3">In average how many times per week do you play?

Secara purata berapa kali anda bermain dalam masa seminggu?</td><td colspan="3"></td></tr>
<tr><td>9</td><td colspan="3">In average how long do you play at once time?

Secara purata berapa lama anda bermain pada sesuatu masa?</td><td colspan="3"></td></tr>
</table>

Causes of sepak takraw ball heading

Kesan-kesan tandukan bola sepak takraw **(Section B)**

INSTRUCTION: The matters listed below are MTBI symptoms that may occur after heading the sepak takraw ball. Please select the appropriate box if you experience any of the symptoms since playing sports sepak takraw.

ARAHAN: Perkara-perkara yang disenaraikan di bawah adalah tanda-tanda yang mungkin berlaku selepas menanduk bola. Sila pilih kotak yang sesuai jika anda mengalami mana-mana gejala sejak bermain sukan sepaktakraw.

No	**Type of Symptoms** *Jenis Gejala*	**Very Agree** *Sangat Setuju*	**Agree** *Setuju*	**Not Agree** *Tidak Setuju*
1	You have a headache after a heading of a high speed sepak takraw ball. *Anda merasa pening (sakit kepala) setelah menanduk bola sepak takraw yang laju*			
2	You feel pain in the neck after heading of a high speed sepak takraw ball. *Anda merasa sakit leher setelah menanduk bola sepak takraw yang laju*			
3	You feel pain in your back after heading of a high speed sepak takraw ball. *Anda merasa sakit belakang setelah menanduk bola sepak takraw yang laju*			
4	You are difficult to sleep at night after playing sepak takraw game *Anda sukar untuk tidur di waktu malam setelah bermain sepak takraw*			
5	You feel weak after the heading sepak takraw ball *Anda merasa lemah setelah menanduk bola sepak takraw*			

6	You have problems with your memory *Apakah anda merasa ada masalah dengan ingatan*			
7	You forget where you put things (everyday). *Anda pernah lupa dimana letak sesuatu barang (seharian)*			
8	You have difficulty to focusing in following the sepak takraw game in progress *Anda susah untuk mengikuti jalannya pertandingan sepak takraw*			
9	You have difficulty in focusing (everyday) *Anda ada kesulitan penumpuan perhatian (seharian)*			
10	You have problems in starting a sepak takraw game *Anda masalah bila memulakan permainan sepak takraw*			
11	You have a blurry vision after heading the sepak takraw ball *Penglihatan anda kabur setelah menanduk bola sepak takraw*			
12	You feel nauseated (want to vomit) after heading of a high speed sepak takraw ball. *Anda rasa mual, nak muntah-muntah setelah menanduk bola sepak takraw yang laju*			
13	You feel sleepy after heading of a high speed sepak takraw ball. *Anda merasa mengantuk setelah menanduk bola sepak takraw yang laju*			

14	You feel confused after heading of a high speed sepak takraw ball (in a few second) *Anda merasa bingung setelah menanduk bola sepak takraw yang laju (beberapa saat)*			
15	You have tears coming out of your eyes after heading of a high speed sepak takraw ball *Anda keluar air mata / menangis setelah menanduk bola sepak takraw yang laju*			
16	You feel emotional after heading of a high speed sepak takraw ball *Anda merasa emosional setelah menanduk bola sepak takraw yang laju*			
17	You find your vision to be doubled *Anda merasa mata penglihatan berganda setelah menanduk bola yang laju*			
18	You have hearing problems *Anda merasa ada ganguan pendengaran*			
19	You hear sounds of droning in your ears after heading of a high speed sepak takraw ball *Anda merasa bunyi ditelinga setelah menanduk bola sepak takraw yang laju*			
20	Your eyes feel sensitive toward bright lights after heading *Anda merasa peka terhadap cahaya terang setelah menanduk bola sepak takraw*			
21	Your ears feel sensitive toward loud noises *Anda merasa peka terhadap suara keras*			

22	You feel unbalanced after heading of a high speed sepak takraw ball *Anda susah untuk seimbang setelah menanduk bola yang laju*			

Position of Heading of Sepak Takraw Ball on the Head

Posisi tandukan bola sepak takraw di kepala (Section C)

1. Do you ever wear a head covering (Headband): (Yes / No)

   Adakah anda pernah memakai pelindung kepala (headband): (Ya/ Tidak)

   If (yes) type of head covering material you normally use and purpose you wear:

   Jika (ya) jenis bahan (material) pelindung kepala yang anda biasa gunakan dan tujuan anda memakainya:

	1. *Kain* (Cotton)
	2. *Kain* (polyester)
	3. *Getah* berkain (rubber fabric)
	4. Please fill in if other materials *Sila isi jika bahan lain*:
Tujuan	

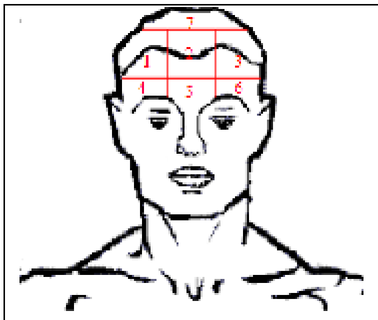
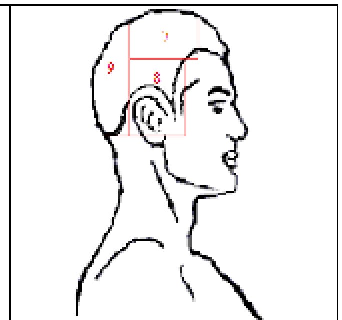
2. How often do you heading the sepak takraw ball in one day training session

   Berapa kerapkah anda menanduk bola sepak takraw dalam satu sesi hari latihan

	0 - 20 times *(kali)*		61 - 80 times *(kali)*
	21 - 40 times *(kali)*		81 - 100 times *(kali)*
	41 - 60 times *(kali)*		Please fill in an amount exceeding 101 times *Sila isi jika melebihi 101 kali* : ___________

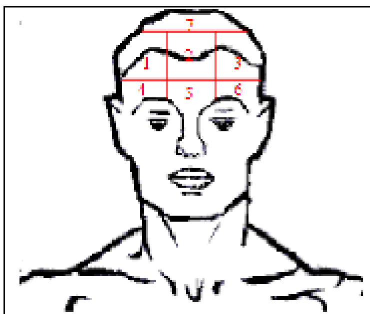
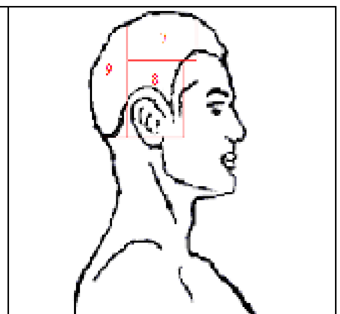
3. Please indicate in the diagram below for your heading area of the sepak takraw ball (can tick more than one)

   Sila tandakan gambar rajah dibawah ini untuk kawasan anda menanduk bola sepak takraw (boleh tanda lebih dari satu)

	
Front View	Side view

4. Please indicate in the diagram below the area of the head that you feel the pain (headache) when heading the sepak takraw ball (can tick more than one)

   Sila tandakan gambar rajah dibawah ini untuk kawasan kepala yang anda rasa sakit saat menanduk bola sepak takraw (boleh tanda lebih dari satu)

	
Front View	Side view

5. Are you moving the head (reply header) when the sepak takraw ball at the fast of service?

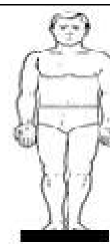
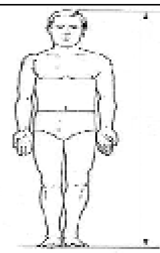
   Adakah anda mengerakan kepala (membalas tandukan) pada saat menanduk bola takraw pada saat servis yang laju?

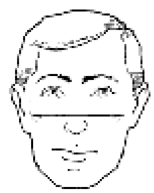
   a. Yes *(Ada)* b. No *(Tidak)* c. Sometimes *(Sekali-sekala)*

Additional Comment:

APPENDIX B

Measurement of Anthropometric for the players

No	Segment	Figures	Description	Tool
1	Weight		Weight of the body	Weight scale
2	Stature		The vertical distance between the standing surface and the top of the head.	Anthropometric rod
3	Head length		Maximum length of the head between the glabella landmark and the opisthocranion	Sliding Caliper
4	Head breadth		Maximum horizontal breadth of the head above the attachment of the ears	Sliding Caliper
5	Tragion to top of head		Vertical distance between the tragion landmark on the cartilaginous flap in front of the ear hole and the horizontal plane tangent to the	Clipper

			top of the head	
6	Menton-sellion length (face length)		The distance between the tip of the chin (menton) and the deepest point of the nasal root depression (sellion).	Sliding Caliper
7	Bizygomatic breadth (face breadth)		The horizontal distance between the maximum protrusions of the cheekbones (zygomatic arches).	Sliding Caliper
8	Interpupillary breadth		Horizontal distance between the two pupils	Sliding Caliper
9	Head circumference		The maximum circumference of the head above the browridges and ears.	Measuring tape
10	Neck circumference		Circumference of the neck at the infrathyroid landmark (Adam's apple)	Measuring tape

APPENDIX C

List of Publications

The present study has been published in the following journals and proceedings:

1. Norhafizan Ahmad, Zahari Taha, Tuan Mohammad Yusoff Shah Tuan Ya and Iskandar Hasanuddin, Finite Element Simulation of Takraw Balls and Their Impact on a Flat Surface, *Movement, Health & Exercise,* a sport journal by Ministry Higher Education, Malaysia, 1(1), 1-9, 2012.

2. Zahari Taha, Iskandar Hasanuddin, Tuan Mohammad Yusoff Shah Tuan Ya, Norhafizan Ahmad and Raja Ariffin Raja Ghazila, Estimation of Head Impact Power on Sepak Takraw Players using Photogrametrics Method. *The 11th Asia Pacific Industrial Engineering & Management Systems Conference*, Melaka, Malaysia (ISBN: 978-967-5148-80-4) 2010.

3. Zahari Taha , Iskandar and Hilma, A Study of the Impact of Sepak takraw Balls on the Head, ISSN 1750-9823, *International Journal of Sports Science and Engineering* Vol. 02 No. 02, pp. 107-110, 2008.

4. Iskandar Hasanuddin; Zahari Taha; Raja Ariffin Raja Ghazila; Novita Sakundarini "Comparison of motion data from video cameras and accelerometer

of human running", *The 9th Asia Pacific Industrial Engineering & Management Systems Conference*, Bali, Indonesia, 2008.

APPENDIX D

Video of data from championships, experiments and FE simulations are available in the CD attached to thesis:

1. Front-Forehead heading from championship
2. Top-Forehead heading from championship
3. Side-Forehead heading from championship
4. Gajah Emas Ball of drop-test on the skull dummy
5. Marathon Ball of drop-test on the skull dummy
6. Salim Ball of drop-test on the skull dummy
7. Subject heading of drop test on Salim ball (experiment in laboratory)
8. FE simulation of drop-test on skull dummy
9. FE simulation of drop-test on skull dummy(cross-sectional view)
10. FE simulation of front-forehead heading
11. FE simulation of front-forehead heading (cross-sectional view)
12. FE simulation of top-forehead heading
13. FE simulation of top-forehead heading (cross-sectional view)
14. FE simulation of side-forehead heading
15. FE simulation of side-forehead heading (cross-sectional view)